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Inventor(s)	:	**Lutz MAY** **Wolfratshauser Str. 23a** **82578 Geretsried-Gelting** **Germany** **Citizenship: Germany**
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1. **1** sheet of Title Page and **66** sheets of Specification.
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Date: October 12, 2004

By: ______________________
Oleg F. Kaplun (Reg. No. 45,559)

Fay Kaplun & Marcin, LLP
150 Broadway, Suite 702
New York, NY 10038

[40124/04001]

U.S. PROVISIONAL PATENT APPLICATION

For

METHOD AND AN ARRAY FOR ADJUSTING A MAGNETIZATION OF A MAGNETIZABLE OBJECT, AND THE USE OF AT LEAST ONE ACTIVATIBLE DEGAUSSING ELEMENT TO DEGAUSS A PART OF A MAGNETIZED PORTION OF AN OBJECT

Inventor(s):

Lutz MAY

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Represented by:
FAY KAPLUN & MARCIN, LLP
150 Broadway, Suite 702
New York, NY 10038
(212) 619-6000 (tel)
(212) 619-0276 (fax)
info@FKMiplaw.com

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Name: Oleg F. Kaplun, Reg. No. 45,559

Signature

A method and an array for adjusting a magnetization of a magnetizable object, and the use of at least one activatible degaussing element to degauss a part of a magnetized portion of an object

Background of the Invention

Field of the Invention

The present invention relates to a method and to an array for adjusting a magnetization of a magnetizable object, and to the use of at least one activatable degaussing element to degauss a part of a magnetized portion of an object .

Description of the Related Art

Magnetic transducer technology finds application in the measurement of torque and position. It has been especially developed for the non-contacting measurement of torque in a shaft or any other part being subject to torque or linear motion. A rotating or reciprocating element can be provided with a magnetized region, i.e. a magnetic encoded region, and when the shaft is rotated or reciprocated, such a magnetic encoded region generates a characteristic signal in a magnetic field detector (like a magnetic coil) enabling to determine torque or position of the shaft.

For such kind of sensors which are disclosed, for instance, in WO 02/063262, it is important to have a magnetically encoded region extending along a spatially accurately defined portion of the shaft. However, when a part of a shaft is magnetized in longitudinal direction, as described in WO 02/063262, it may happen that a region at the border between a non-magnetized portion and a magnetized portion of the shaft does not have well-defined magnetic properties. In

other words, a magnetization may be obtained in such a border area which has intermediate values between the magnetization of the non-magnetized and the magnetization of the magnetized portion. Such a non-well defined region deteriorates the sensitivity of a torque sensor or a position sensor, since it has an influence to the detection signal captured by a magnetic field detector.

Summary of the Invention

It is an object of the present invention to accurately define magnetized and unmagnetized portions of a magnetizable object.

This object is achieved by providing a method and an array for adjusting a magnetization of a magnetizable object, and by using at least one activatable degaussing element to degauss a part of a magnetized portion of an object according to independent aspects of the invention mentioned in the following.

In the following, different aspects of the invention will be described.

Aspects 1, 21, and 32 are independent aspects of the invention which may be realized with or without any other means. Aspects 2 to 20 relate to preferred embodiments of aspect 1. Aspects 22 to 31 relate to preferred embodiments of aspect 21.

1. aspect: A method for adjusting a magnetization of a magnetizable object, the method comprising the steps of

providing an object having a magnetized portion extending along at least a part of the object;

arranging at least one degaussing element adjacent to the magnetized portion;

degaussing a part of the magnetized portion by activating the degaussing element to adjust the magnetization of the magnetizable object by forming a demagnetized portion of the object directly adjacent to a remaining magnetized portion of the object.

2. aspect: The method according to aspect 1, wherein an object is provided having the magnetized portion extending along the entire object.

3. aspect: The method according to aspect 1, wherein an object is provided having a plurality of alternating magnetized and unmagnetized portions.

4. aspect: The method according to any of aspects 1 to 3, wherein at least one the at least one degaussing element is a degaussing coil.

5. aspect: The method according to aspect 4, wherein the degaussing coil is arranged to surround a portion of the magnetized portion to be demagnetized.

6. aspect: The method according to any of aspects 1 to 5, wherein at least one the at least one degaussing element is an electromagnet.

7. aspect: The method according to any of aspects 4 to 6, wherein the at least one degaussing element is activated by applying a time-varying electric signal.

8. aspect: The method according to any of aspects 4 to 7,

wherein the at least one degaussing element is activated by applying an alternating current or an alternating voltage.

9. aspect: The method according to aspect 8, wherein the alternating current or the alternating voltage alternates with a frequency which is substantially smaller than 50 Hz.

10. aspect: The method according to aspect 8 or 9, wherein the alternating current or the alternating voltage alternates with a frequency less than 5 Hz.

11. aspect: The method according to any of aspects 1 to 10, wherein at least one the at least one degaussing element is a permanent magnet.

12. aspect: The method according to aspect 11, wherein the permanent magnet is activated by moving the permanent magnet in the vicinity of the object in a time-varying manner.

13. aspect: The method according to any of aspects 1 to 12, wherein the magnetized portion of the object is formed by magnetizing magnetizable material of the object by activating a magnetizing coil which is arranged to surround the portion of the object to be magnetized.

14. aspect: The method according to aspect 13, wherein the magnetizing coil is activated by applying a direct current or a direct voltage.

15. aspect: The method according to any of aspects 1 to 12, wherein the magnetized portion of the object is formed by

applying at least two current pulses to the object such that in a direction essentially perpendicular to a surface of the object, a magnetic field structure is generated such that there is a first magnetic flow in a first direction and a second magnetic flow in a second direction, wherein the first direction is opposite to the second direction.

16. aspect: The method according to aspect 15, wherein, in a time versus current diagram, each of the at least two current pulses has a fast raising edge which is essentially vertical and has a slow falling edge.

17. aspect: The method according to any of aspects 1 to 16, wherein a shaft is provided as the object.

18. aspect: The method according to aspect 17, wherein the shaft is one of the group consisting of an engine shaft, a reciprocable work cylinder, and a push-pull-rod.

19. aspect: The method according to any of aspects 1 to 18, wherein only one of the at least one degaussing element is activated at a time.

20. aspect: The method according to any of aspects 1 to 18, wherein at least two degaussing elements are activated at a time.

21. aspect: An array for adjusting a magnetization of a magnetizable object, comprising:

an object having a magnetized portion extending along at least a part of the object;

at least one degaussing element arranged adjacent to the magnetized portion, the at least one degaussing element being

adapted to be activated to degauss a part of the magnetized portion to adjust the magnetization of the magnetizable object by forming a demagnetized portion of the object directly adjacent to a remaining magnetized portion of the object.

22. aspect: The array according to aspect 21, wherein the object is a shaft.

23. aspect: The array according to aspect 22, wherein the shaft has a first unmagnetized portion and a second unmagnetized portion, the magnetized portion being arranged between the first unmagnetized portion and the second unmagnetized portion.

24. aspect: The array according to aspect 23, having a first degaussing coil and having a second degaussing coil as degaussing elements, the first degaussing coil being arranged surrounding a portion of the magnetized portion adjacent the first unmagnetized portion, and the second degaussing coil being arranged surrounding a portion of the magnetized portion adjacent the second unmagnetized portion.

25. aspect: The array according to aspect 24, wherein the first degaussing coil has a first connection and a second connection, and wherein the second degaussing coil has a first connection and a second connection, wherein a first voltage is applyable between the first connection and the second connection of the first degaussing coil, and a second voltage is applyable between the first connection and the second connection of the second degaussing coil.

26. aspect: The array according to aspect 24,

wherein the first degaussing coil has a first connection and a second connection, and wherein the second degaussing coil has a first connection and a second connection, wherein a voltage is applyable between the first connection of the first degaussing coil and the second connection of the second degaussing coil, wherein the second connection of the first degaussing coil is coupled with the first connection of the second degaussing coil.

27. aspect: The array according to any of aspects 24 to 26, having a first stopper coil and having a second stopper coil, the first stopper coil being arranged surrounding a portion of the magnetized portion adjacent the first degaussing coil, and the second stopper coil being arranged surrounding a portion of the magnetized portion adjacent the second degaussing coil in such a manner that the first and second stopper coils are arranged between the first and second degaussing coils, wherein such an electrical signal can be applied to the first and the second stopper coils that a region between the first and second stopper coils is prevented from being demagnetized when at least one of the at least one degaussing element is magnetized.

28. aspect: The array according to any of aspects 21 to 27, wherein the magnetized portion is a longitudinally magnetized region of the object.

29. aspect: The array according to any of aspects 21 to 27, wherein the magnetized portion is a circumferentially magnetized region of the object.

30. aspect: The array according to any of aspects 21 to 29,

wherein the magnetized portion is formed by a first magnetic flow region oriented in a first direction and by a second magnetic flow region oriented in a second direction, wherein the first direction is opposite to the second direction.

31. aspect: The array according to aspect 30, wherein, in a cross-sectional view of the object, there is the first circular magnetic flow having the first direction and a first radius and the second circular magnetic flow having the second direction and a second radius, wherein the first radius is larger than the second radius.

32. aspect: Using at least one activatable degaussing element to degauss a part of a magnetized portion of an object to adjust the magnetization of the magnetizable object by forming a demagnetized portion of the object directly adjacent to a remaining magnetized portion of the object.

In the following, the above mentioned independent aspects of the invention will be described in more detail.

One idea of the invention may be seen in the fact that a magnetized object (e.g. magnetized with a treatment according to WO 02/063262) undergoes a post-treating in which an exactly definable border area between a magnetized region and a non-magnetized region of the magnetizable object is securely demagnetized to obtain a step-like spatial dependency in the magnetization which allows to separates a magnetized region from a non-magnetized region. For this purpose, a degaussing element like a coil is arranged adjacent to the magnetized portion to define the portion to be demagnetized and is degaussed by activating the degaussing element to form a well-defined demagnetized portion which is

arranged directly next to a remaining magnetized portion. Thus, the invention allows a fine-tuning of the magnetization profile along the length of the object. A gradual transition of the magnetization profile along an extension of the object is thus eliminated and replaced by a step-like magnetization profile. Thus, the magnetization properties are fine-tuned and may be adjusted to special requirements for a position sensor, or a torque sensor, increasing the sensitivity of the respective sensor.

The invention introduces the use of a degaussing element, preferably a magnetic coil, wherein the magnetic coil may be slid along the object (e.g. a magnetizable shaft, for instance made of a magnetizable steel). The magnetic coil is slid at such a position of the previously magnetized object that only such a part of the object which shall be demagnetized is located inside the coil opening. Then, an activating current is applied to the coil which has such an orientation, time dependence and strength that the elementary magnets of the portion to be demagnetized are at least partially randomized. Since a portion of the object arranged within the coil can be properly separated from a portion outside the coil, the spatial arrangement of a demagnetized portion and a of a remaining magnetized portion can be separated with high accuracy.

The concept of the invention to degauss a part of a partially magnetized object by surrounding a portion to be demagnetized with a magnetic coil as a degaussing element can be applied to a longitudinally magnetized shaft as disclosed by WO 02/063262, or can be alternatively applied to an object which has previously been magnetized according to the so-called PCME technology ("Pulse Current Modulated Encoding").

The PCME technology will be described in detail below and allows, by introducing a pulse current to the shaft, to generate, inside the object, an inner magnetized region which is surrounded by an outer magnetized region, wherein the magnetization direction of the two regions are oppositely to one another.

Such a magnetization configuration can be achieved by applying a pulse current directly to a predefined portion of a shaft as an example for the object. An effectively used encoding portion is defined by the positions on a shaft at which the current for forming a circumferential magnetic field are applied. The fine-tuning of such an encoding region is achieved with the method of the invention in which a border of the magnetized region in which the magnetization gradually decreases from a high value to zero is transformed into an almost step-like magnetization profile by applying a degaussing signal to a degaussing element.

In the following, preferred embodiments of the method for adjusting a magnetization of a magnetizable object according to the first independent aspect of the invention will be described. However, these embodiments also apply for the array for adjusting a magnetization of a magnetizable object and to the use of at least one activatable degaussing element to degauss a part of a magnetized portion of an object, according to other independent aspects of the invention.

According to the method of the invention, an object may be provided having the magnetized portion extending along the entire object. According to this embodiment, first, the entire object is magnetized, and then a remaining magnetized

portion is defined by demagnetizing selectable portions of the previously entirely magnetized object.

Alternatively, an object may be provided having a plurality of alternating magnetized and unmagnetized portions. According to this configuration, which is particularly advantageous for a position sensor of a reciprocating object wherein the position sensing is realized by measuring the magnetic field generated by the different magnetic regions of the reciprocating object, the object (like a reciprocating shaft) may first be magnetized in selectable portions, and afterwards the invention is implemented to fine-tune the magnetization of the sequence of magnetized and non-magnetized regions, by generating a magnetization profile which follows a mathematical step function.

At least one of the at least degaussing elements may be a degaussing coil. With a degaussing coil, i.e. a magnetic coil, the region of demagnetization can be properly defined by sliding the coil along the object, for instance a shaft.

Thus, the degaussing coil may be arranged to surround a portion of the magnetized portion to be demagnetized. This allows a proper positioning and definition of the region of the magnetized object to be demagnetized.

At least one of the at least one degaussing element may be an electromagnet. Using an electromagnet being controlled to form a time-dependent magnetic field is an alternative to a magnetic coil. Since an electromagnet can be provided in different shapes, sizes and geometries, it is also very suitable to properly define a portion to be demagnetized.

At least one of the degaussing elements may be activated by applying a time-varying electric signal. A time-varying electric signal (for instance an alternating current or an alternating voltage) produces a time-dependent magnetic field which, applied to a magnetized portion, may randomize the ordered magnetized elementary magnets, thus achieving a secure demagnetization.

Particularly, the at least one degaussing element may be activated by applying an alternating current or an alternating voltage.

The alternating current or the alternating voltage alternates preferably with a frequency which is substantially smaller than 50 Hz. Due to the so-called skin effect, it is preferred to use a sufficiently small frequency to allow a proper demagnetization also in the inner parts of the object, for instance close to the center of a shaft. This can be achieved by using sufficiently small frequencies, wherein, in a first approximation, the frequency value can be selected to be inversely proportional to the cross-sectional area of the object.

Thus, a proper value for the frequency of the time-varying demagnetization signal sensitively depends on the application used, but such a frequency is preferably considerably smaller than 50 Hz. For instance, a frequency region between 0.01 Hz and 20 Hz is suitable, a particularly preferred range is between 0.01 Hz and 5 Hz. When selecting parameters defining the degaussing signal, there is an interplay between time, amplitude and frequency of the applied electrical signal (e.g. voltage or current). As a rule of thumb, the demagnetization should be continued until an almost complete

randomization of the elementary magnets of the magnetized region to be demagnetized is achieved.

Further preferable, the alternating current or the alternating voltage may alternate with a frequency less than 5 Hz.

As an alternative to a configuration in which the degaussing element is realized as a coil or as an electromagnet, a permanent magnet may be used as degaussing element and may be activated by moving the permanent magnet in the vicinity of the object in a time-varying manner. By such a motion (e.g. a mechanical oscillation), a time-dependent demagnetization field is effective to the portion of the object to be demagnetized. Such a configuration makes the use of electrical degaussing signals indispensable, since a pure mechanical degaussing sequence is possible using a permanent magnet.

The magnetized portion of the object may be formed by magnetizing magnetizable material of the object by activating a magnetizing coil which is arranged to surround the portion of the object to be magnetized. Such a technology of magnetizing an object is disclosed, for instance, in WO 02/063262. According to this magnetization sequence, a portion of a magnetizable object (e.g. a metallic object like a shaft made of industrial steel) may be magnetized, wherein quality problems may occur at the border between the magnetized region and a non-magnetized region. Such a shaft may then be treated according to the fine-tuning of the magnetization profile according to the invention to improve the transition between magnetized and unmagnetized regions.

According to the described aspect, the magnetizing coil may be activated by applying a direct current or a direct voltage.

Alternatively to the magnetization method of WO 02/063262, the so-called PCME technology ("Pulse Current Modulated Encoding") technology may be applied, which will be described in detail below. According to this technology, the magnetized portion of the object may be formed by applying at least two current pulses to the object such that in a direction essentially perpendicular to a surface of the object, a magnetic field structure is generated such that there is a first magnetic flow in a first direction and a second magnetic flow in a second direction, wherein the first direction is opposite to the second direction. According to this magnetization scheme, in a time versus current diagram, each of the at least two current pulses has a fast raising edge which is essentially vertical and has a slow falling edge.

As the object, a shaft may be provided. Particularly, the shaft may be one of the group consisting of an engine shaft, a reciprocatable work cylinder, and a push-pull-rod.

Such an engine shaft may be used in a vehicle like a car to measure the torque of the engine. A reciprocatable work cylinder may be used in a concrete (cement) processing apparatus wherein one or more magnetically encoding regions on such a reciprocating work cylinder may be used to determine the actual position of the work cylinder within the concrete processing apparatus to allow an improved control of the operation of the reciprocating cylinder. A push-pull-rod, or a plurality of push-pull-rods, may be provided in a gear

box of a vehicle and may be provided with one or more magnetic encoded regions to allow a position detection of the push-pull-rod.

Preferably, only one of the at least one degaussing element is activated at a time. By activating each of the degaussing elements separately and one after another, the fine-tuning of the magnetization can be performed with a very high accuracy, and regions to remain magnetized are prevented from being demagnetized.

Alternatively, at least two degaussing elements may be activated at a time. This configuration allows a very fast fine-tuning and is therefore a very cost effective alternative.

In the following, preferred embodiments of the array for adjusting a magnetization of a magnetizable object according to the second independent aspect of the invention will be described. However, these embodiments also apply for the method for adjusting a magnetization of a magnetizable object and to the use of at least one activatable degaussing element to degauss a part of a magnetized portion of an object according to other independent aspects of the invention.

In the array, the object may be a shaft.

The shaft may have a first unmagnetized portion and may have a second unmagnetized portion, the magnetized portion being arranged between the first unmagnetized portion and the second unmagnetized portion.

The array may have a first degaussing coil and may have a second degaussing coil as degaussing elements, wherein the first degaussing coil may be arranged surrounding a portion of the magnetized portion adjacent the first unmagnetized portion, and the second degaussing coil may be arranged surrounding a portion of the magnetized portion adjacent the second unmagnetized portion.

The first degaussing coil may have a first connection and may have a second connection. The second degaussing coil may have a first connection and may have a second connection. A first voltage may be applied between the first connection and the second connection of the first degaussing coil, and the second voltage may be applied between the first connection and the second connection of the second degaussing coil. In other words, according to this configuration, the two degaussing coils are electrically decoupled from one another. Thus, demagnetization signals for two borders between magnetized and unmagnetized portions may be generated one after another, yielding a high quality of the produced magnetization profile.

Alternatively, the first degaussing coil may have a first connection and may have a second connection, and the second degaussing coil may have a first connection and a second connection. A voltage may be applied between the first connection of the first degaussing coil and the second connection of the second degaussing coil, wherein the second connection of the first degaussing coil may be coupled with the first connection of the second degaussing coil. According to this configuration, a single voltage and thus a single voltage supply is sufficient to operate the array, since two connections of the degaussing coils are coupled allowing to

simultaneously produce a demagnetization signal for two borders between magnetized and unmagnetized portions.

Further, the array of the invention may have a first stopper coil and may have a second stopper coil, the first stopper coil being arranged surrounding a portion of the magnetized portion adjacent the first degaussing coil, and the second stopper coil may be arranged surrounding a portion of the magnetized portion adjacent the second degaussing coil in such a manner that the first and second stopper coils are arranged between the first and second degaussing coils. Such an electrical signal can be applied to the first and the second stopper coils that the region between the first and second stopper coils are prevented from being demagnetized when the degaussing elements are activated. According to this configuration, small stopper coils or stopper inductors may be placed at a specific end of the degaussing elements, and the inductivity of the stopper coils may be significantly lower than the inductivity of the degaussing coils. Thus, the area which is affected by the demagnetization procedure can be defined even better.

The magnetized portion may be a longitudinally magnetized region of the object, for instance generated according to the technology described in WO 02/063262.

Alternatively, the magnetized portion may be a circumferentially magnetized region of the reciprocating object. This can be achieved by implementing the so-called PCME technology described below.

According to the latter aspect, the magnetized portion may be formed by a first magnetic flow region oriented in a first

direction and by a second magnetic flow region oriented in a second direction, wherein the first direction is opposite to the second direction. Thus, in a cross-sectional view of the object, there may be the first circular magnetic flow having the first direction and a first radius, and the second circular magnetic flow may have the second direction and a second radius, wherein the first radius may be larger than the second radius.

The above and other aspects, objects, features and advantages of the present invention will become apparent from the following description and the appended claim, taken in conjunction with the accompanying drawings in which like parts or elements are denoted by like reference numbers.

Brief Description of the Drawings

The accompanying drawings, which are included to provide a further understanding of the invention and constitute a part of the specification illustrate embodiments of the invention.

In the drawings:

Fig.1 to **Fig.7** show different views of a magnetizable shaft during a method for adjusting the magnetization of the shaft according to an embodiment of the invention.

Fig.8 shows an array for adjusting a magnetization of a shaft according to a first embodiment of the invention.

Fig.9 shows an array for adjusting a magnetization of a shaft according to a second embodiment of the invention.

Fig.10A, **Fig.10B** show an array for adjusting a magnetization of a shaft according to a third embodiment of the invention.

Fig.10C shows an array for adjusting a magnetization of a shaft according to a forth embodiment of the invention.

Fig.11A to **Fig.11C** show schemes for illustrating the invention.

Fig.12 to **Fig.67** illustrate the PCME technology which, according to the invention, is preferably used to magnetize a magnetizable object.

Detailed Description of Preferred Embodiments of the Invention

In the following, referring to Fig.1 to Fig.7, a method for adjusting a magnetization of a magnetizable object according to the invention will be described.

Fig.1 shows a cylindrical shaft 100 which is made of magnetizable industrial steel.

However, according to the scenario shown in Fig.1, the steel shaft 100 is demagnetized.

Fig.2 shows a configuration in which the magnetizable shaft 100 is partially magnetized, by the so-called PCME technology. For this purpose, a first metallic ring 200 is applied directly to the magnetizable shaft 100, and a second metallic ring 201 is attached to another part of the shaft

100. Then, a pulse electric current I_1 is applied to the rings 200, 201 to magnetize a portion 202 of the shaft 100. The magnetized portion 202 of the shaft 100 is formed by applying two current pulses to the shaft 100, each of the current pulses having a fast railing edge and a slow falling edge, such that in a direction essentially perpendicular to a surface of the shaft 100, a magnetic field structure is generated such that there is a first magnetic flow in a first direction and a second magnetic flow in a second direction, wherein the first direction is opposite to the second direction. In a time versus current diagram, each of the at least two current pulses has a fast raising edge which is essentially vertical and has a slow falling edge.

Fig.2 also shows schematic current paths 203 which are strongly curved in a vicinity of the rings 200, 201. Thus, the magnetization is not very homogeneous in a portion directly neighbouring the rings 200, 201.

Fig.3 shows schematically a cross-section of the shaft 100, wherein, in a portion in which beforehand the (now removed) rings 200, 201 had been attached, a magnetized region 202 is generated. The shaft 100 has a first unmagnetized portion 301 and has a second unmagnetized portion 302, the magnetized portion 202 being arranged between the first unmagnetized portion 301 and the second unmagnetized portion 302. As can be seen in Fig.3, the magnetized portion 202 is formed by a first magnetic flow region 303 oriented in a first direction 305 and by a second magnetic region 304 oriented in a second direction 306, wherein the first direction 305 is opposite to the second direction 306. As can further be seen in Fig.3, in a cross-sectional view of the shaft 100, the first circular magnetic flow 303 has the first direction 305 and a first

radius, and the second circular magnetic flow 304 has the second direction 306 and a second radius, wherein the first radius is larger than the second radius.

However, when using the magnetized portion 202 as a magnetically encoded region for a torque sensor or a position sensor, only the central part of the magnetized region 202 can be used with for a high quality application, since only here the magnetization is homogeneous, whereas the magnetization is quite inhomogeneous at a border between one of the demagnetized regions 301, 302 and the magnetized region 202, i.e. a portion at which previously the rings 200, 201 had been attached.

As can be seen in **Fig.4**, the magnetization of the partially magnetized shaft 100 is adjusted by arranging a first degaussing coil 400 (coil axis parallel to shaft axis) adjacent the magnetic portion 202, i.e. at the border between the first unmagnetized portion 301 and the magnetized portion 202. Further, a second degaussing coil 401 (coil axis parallel to shaft axis) is arranged at a border between the magnetized region 202 and the second unmagnetized region 302.

As can be further seen in Fig.4, the part of the magnetized portion 202 being covered by the first degaussing coil 400 is degaussed and thus demagnetized by activating the first degaussing coil 400 to adjust the magnetization of the magnetizable shaft 100 by forming a demagnetized portion 500 of the shaft 100 directly adjacent to a remaining magnetized portion 501 of the shaft 100. Further referring to Fig.4, this is achieved by applying an alternating current I_2 to the first degaussing coil 400 with a frequency of 1 Hz. Thus, the elementary magnets within the demagnetized portion 500 are

almost randomized to eliminate any magnetization in this region. At the border between the demagnetized portion 500 and the remaining magnetized portion 501 of the shaft 100, the magnetization profile can be described by a step function, since the part of the shaft 100 to be demagnetized is clearly defined.

Referring to **Fig.5**, the demagnetization procedure is repeated with the portion to be demagnetized between the magnetized region 200 and the second unmagnetized region 302. For this purpose, an alternating current I_3 is applied to the second degaussing coil 401 to generate a second demagnetized portion 600, to define a remaining magnetized portion 601 which is spatially clearly defined.

After removing the degaussing coils 400, 401, the configuration of **Fig.7** is obtained showing a remaining magnetized region 601 in the center of the shaft 100, having two circumferential magnetized portions 303, 304 with oppositely oriented magnetizing directions.

In the following, referring to **Fig.8**, an array 800 for adjusting a magnetization of a shaft 100 according to a first embodiment of the invention will be described.

The array 800 for adjusting a magnetization of a magnetizable shaft 100 comprises the shaft 100 having a magnetized portion (not shown) extending along a part of the shaft 100. In the scenario of Fig.8, the magnetized portion extends along the part of the shaft 100 extending between a first degaussing coil 801 and a second degaussing coil 802. The part of the shaft 100 being magnetized has previously been magnetized according to the PCME technology. A part of the magnetized

portion is covered by the coils 801, 802 and will be demagnetized, as described in the following.

The first degaussing coil 801 is arranged adjacent to the magnetized portion, and the second degaussing coil 802 is arranged adjacent to the magnetized portion. Thus, the shaft 100 has a first unmagnetized portion and a second unmagnetized portion, the magnetized portion being arranged between the first unmagnetized portion and the second unmagnetized portion. The first degaussing coil 801 is arranged surrounding a portion of the magnetized portion adjacent the first unmagnetized portion, and the second degaussing coil 802 is arranged surrounding a portion of the magnetized portion adjacent the second unmagnetized portion. The first degaussing coil 801 has a first connection 803 and a second connection 804, and the second degaussing coil 802 has a first connection 805 and has a second connection 806. A voltage can be applied between the first connection 803 of the first degaussing coil 801 and the second connection 806 of the second degaussing 802. The second connection 804 of the first degaussing 801 is coupled with the first connection 805 of the second degaussing coil 802.

In the following, the method of demagnetizing a portion of the magnetized portion of the shaft 100 will be described.

Applying a PCME electrical encoding pulse to the shaft 100 turned a large part of the shaft 100 into a sensing element. While this has the benefit that the sensor performance is a highest (at the center of the shaft 100), it has the disadvantage that the shaft 100 being largely magnetized is very "hot spotting" sensitive, i.e. sensitive to a nearby ferromagnetic material.

This means that a large part of the shaft 100, almost from end to end, is sensitive to applied mechanical forces. Equally, the resulting magnetic field changes at the shaft 100 surface, stretch over the entire shaft 100 length. Such a dimensionally large magnetic field can be easily attracted or influenced in shaped by other ferromagnetic devices that are placed (or moved) near the magnetically encoded shaft 100.

Therefore, the magnetic encoded region should in axial direction kept reasonably short. Even better it will be to place pinning fields in either side of the magnetically encoded region. In the example shown in Fig.8, a large part of the shaft 100 has been magnetically encoded, and subsequently, the magnetic encoding will be deleted on either side of the desired location of the remaining magnetized portion of the torque sensor shaft 100.

According to embodiment shown in Fig.8, this is achieved by sliding the shaft ends into a radially tightly wound coil (inductor) 801, and 802, respectively. By applying an alternating electrical current through the inductors 801, 802, the magnetic sensor encoding will be reduced in strength, or even entirely erased. As can be seen, the field cancellation efficiency is almost 100% in the region of the shaft 100 which is surrounded by the degaussing coils 801, 802, and is smaller in the center of the shaft 100.

However, as seen in Fig.8, applying the alternating current to both coils 801, 802 at the same time will to a larger degree have an effect also on the sensor region that lies between the two erasing coils 801, 802. With other words, this approach will not only delete the magnetic encoding at

the shaft ends, but also partially in the middle section of the shaft 100.

Thus, when driving the magnetic field cancellation inductors 801, 802 simultaneously, the magnetic field cancellation efficiency is stretching beyond the location where the magnetic field cancellation inductors 801, 802 end. Consequently, the section between the degaussing coils 801, 802 will also be affected. This means that the magnetic encoding that may have been present in the section between the degaussing coils 801, 802 will be, to some extent, erased as well.

In the following, referring to **Fig.9**, an array 900 for adjusting a magnetization of the shaft 100 according to a second embodiment of the invention will be described, which is further improved compared to the embodiment shown in Fig.8.

According to Fig.9, only one of the coils 801, 802 at one time is connected to the alternating electrical current. In other words, according to Fig.9, a first voltage may be applied between the first connection 803 and the second connection 804 of the first degaussing coil 801, and independently from this, a second voltage may be applied between the first connection 805 and the second connection 806 of the second degaussing coil 802, one voltage being applied after the other.

As can be seen from the graph in Fig.9, the field cancellation efficiency is significantly reduced in the area between the coils 801, 802 compared to the array 800, so that the portion related to the remaining magnetization in the

center of shaft 100 is prevented from being demagnetized in an improved manner.

According to Fig.9; even better results are achieved when operating the magnetic field cancellation inductors 801, 802 one after each other. The magnetic field cancellation efficiency is dropping noticeably in the spacing between the two degaussing coils 801, 802. However, the magnetic encoding that may have been present in the section between the two degaussing coils 801, 802 may still be erased to a smaller extent in a non-uniform way.

In the following, referring to **Fig.10A**, an array 1000 for adjusting a magnetization of the shaft 100 according to a third embodiment of the invention will be described.

According to the embodiment shown in Fig.10, the array has a first stopper coil 1001 and has a second stopper coil 1002, the first stopper coil 1001 being arranged surrounding a portion of the magnetized portion adjacent the first degaussing coil 801, and the second stopper coil 1002 is arranged surrounding a portion of the magnetized portio n adjacent the second degaussing coil 802 in such a manner that the first and second stopper coils 1001, 1002 are arranged between (intermediate, i.e. sandwiched between) the first and second degaussing coils 801, 802, wherein such a voltage can be applied to the first and second stopper coils 1001, 1002 that the region between the first and second stopper coils 1001, 1002 is prevented from being demagnetized when the degaussing elements 801, 802 are magnetized.

As can be seen in Fig.10, when using stopper inductors 1001, 1002 (these are inductors that are placed at a specific end

of the magnetic field cancellation inductors 801, 802, and the inductivity of the stopper inductors 1001, 1002 is significantly lower than the inductivity of the magnetic field inductors 801, 802), the area which is affected by the magnetic field cancellation inductors 801, 802 can be much clearer defined. An additional benefit is such that a magnetic field cancellation system design can be operated in one step (no sequential operation of applying voltages is necessary).

As one can see from Fig.10A, **Fig.10B,** a single current signal is applied to the coils 801, 802, 1001, 1002, and the current flows between the first connection 803 of the first degaussing coil 801 and the second connection 806 of the second degaussing coil 802. After having flown through the first degaussing coil 801 and before flowing through the second degaussing coil 802, the current flows through the first stopper coil 1001 and the second stopper coil 1002. However, the flowing direction of the current in the degaussing coils 801, 802 is the same, and the flowing direction of the current in the stopper coils 1001, 1002 is the same. The flowing direction of the current in any of the degaussing coils 801, 802 is opposite to the flowing direction of the current in any of the stopper coils 1001, 1002. The number of windings of each of the degaussing coils 801, 802 is larger than the number of windings of each of the stopper coils 1001, 1002. Thus, the strength of the magnetic field generated by any of the coils 801, 802, 1001, 1002 is adjusted by selecting the number of windings, and by adjusting the amplitude of the applied current, to achieve proper magnetic field values generated by any of the coils 801, 802, 1001, 1002.

In the following, referring to **Fig.10C**, an array 1050 for adjusting a magnetization of the shaft 100 according to a forth embodiment of the invention will be described.

According to the embodiment shown in Fig.10C, each of the coils 801, 802, 1001, 1002 has two connections with separate current sources I_1, I_2, I_3, I_4. Thus, the current to flow through any of the coils 801, 802, 1001, 1002 can be adjusted separately for any of the coils 801, 802, 1001, 1002. The strength of each of these currents may be adjusted individually to allow to set the magnetization profile along the shaft 100 in desired manner. According to the embodiment of Fig.10C, the current values are selected as follows: $I_1=I_4$, $I_2=I_3$, $|I_2|<|I_1|$. According to Fig. 10C, the number of windings (4) is identical for each of the coils 801, 802, 1001, 1002.

In the following, referring to Fig.11A to Fig.11C, a background and explanation for the invention is given.

Fig.11A shows a magnetized shaft 100 and a magnetic field profile 1100 around the shaft 100. When the PCME encoding signal has been applied to the entire shaft, then the magnetized shaft 100 is stretching from end to end.

As can be seen in **Fig.11B**, when a ferromagnetic object 1101 is located in a surrounding area of the magnetized shaft 100, "hot spotting" may occur, i.e. a strong sensitivity to nearby ferromagnetic material 1101. In such a case a magnetic encoded sensor may be (but does not have to be) very sensitive when a ferromagnetic object 1101 will touch one of the shaft 100 ends or is changing its position near the shaft 100. (Example: rotating gear tooth wheel). As can be seen in

Fig.11C, a domino effect can occur. Such effects may be reduced or eliminated by the invention.

In the following, the so-called PCME ("Pulse-Current-Modulated Encoding") Sensing Technology will be described in detail, which can, according to a preferred embodiment of the invention, be implemented to magnetize a magnetizable object which is then partially demagnetized according to the invention. In the following, the PCME technology will partly described in the context of torque sensing. However, this concept may implemented in the context of position sensing as well.

In this description, there are a number of acronyms used as otherwise some explanations and descriptions may be difficult to read. While the acronyms "ASIC", "IC", and "PCB" are already market standard definitions, there are many terms that are particularly related to the magnetostriction based NCT sensing technology. It should be noted that in this description, when there is a reference to NCT technology or to PCME, it is referred to exemplary embodiments of the present invention.

Table 1 shows a list of abbreviations used in the following description of the PCME technology.

Acronym	**Description**	**Category**
ASIC	Application Specific IC	Electronics
DF	Dual Field	Primary Sensor
EMF	Earth Magnetic Field	Test Criteria
FS	Full Scale	Test Criteria
Hot-Spotting		Sensitivity to
nearby Ferro magnetic material		Specification

IC	Integrated Circuit	Electronics
MFS	Magnetic Field Sensor	Sensor Component
NCT	Non Contact Torque	Technology
PCB	Printed Circuit Board	Electronics
PCME	Pulse Current Modulated Encoding	Technology
POC	Proof-of-Concept	
RSU	Rotational Signal Uniformity	Specification
SCSP	Signal Conditioning & Signal Processing	Electronics
SF	Single Field	Primary Sensor
SH	Sensor Host	Primary Sensor
SPHC	Shaft Processing Holding Clamp	Processing Tool
SSU	Secondary Sensor Unit	Sensor Component

Table 1: List of abbreviations

The magnetic principle based mechanical-stress sensing technology allows to design and to produce a wide range of "physical-parameter-sensors" (like Force Sensing, Torque Sensing, and Material Diagnostic Analysis) that can be applied where Ferro-Magnetic materials are used. The most common technologies used to build "magnetic-principle-based" sensors are: Inductive differential displacement measurement (requires torsion shaft), measuring the changes of the materials permeability, and measuring the magnetostriction effects.

Over the last 20 years a number of different companies have developed their own and very specific solution in how to design and how to produce a magnetic principle based torque sensor (i.e. ABB, FAST, Frauenhofer Institute, FT, Kubota, MDI, NCTE, RM, Siemens, and others). These technologies are

at various development stages and differ in "how-it-works", the achievable performance, the systems reliability, and the manufacturing / system cost.

Some of these technologies require that mechanical changes are made to the shaft where torque should be measured (chevrons), or rely on the mechanical torsion effect (require a long shaft that twists under torque), or that something will be attached to the shaft itself (press-fitting a ring of certain properties to the shaft surface,), or coating of the shaft surface with a special substance. No-one has yet mastered a high-volume manufacturing process that can be applied to (almost) any shaft size, achieving tight performance tolerances, and is not based on already existing technology patents.

In the following, a magnetostriction principle based Non-Contact-Torque (NCT) Sensing Technology is described that offers to the user a whole host of new features and improved performances, previously not available. This technology enables the realization of a fully-integrated (small in space), real-time (high signal bandwidth) torque measurement, which is reliable and can be produced at an affordable cost, at any desired quantities. This technology is called: PCME (for Pulse-Current-Modulated Encoding) or Magnetostriction Transversal Torque Sensor.

The PCME technology can be applied to the shaft without making any mechanical changes to the shaft, or without attaching anything to the shaft. Most important, the PCME technology can be applied to any shaft diameter (most other technologies have here a limitation) and does not need to rotate / spin the shaft during the encoding process (very

simple and low-cost manufacturing process) which makes this technology very applicable for high-volume application.

In the following, a Magnetic Field Structure (Sensor Principle) will be described.

The sensor life-time depends on a "closed-loop" magnetic field design. The PCME technology is based on two magnetic field structures, stored above each other, and running in opposite directions. When no torque stress or motion stress is applied to the shaft (also called Sensor Host, or SH) then the SH will act magnetically neutral (no magnetic field can be sensed at the outside of the SH).

Fig.12 shows that two magnetic fields are stored in the shaft and running in endless circles. The outer field runs in one direction, while the inner field runs in the opposite direction.

Fig.13 illustrates that the PCME sensing technology uses two Counter-Circular magnetic field loops that are stored on top of each other (Picky-Back mode).

When mechanical stress (like reciprocation motion or torque) is applied at both ends of the PCME magnetized SH (Sensor Host, or Shaft) then the magnetic flux lines of both magnetic structures (or loops) will tilt in proportion to the applied torque.

As illustrated in **Fig.14**, when no mechanical stresses are applied to the SH the magnetic flux lines are running in its original path. When mechanical stresses are applied the

magnetic flux lines tilt in proportion to the applied stress (like linear motion or torque).

Depending on the applied torque direction (clockwise or anti-clockwise, in relation to the SH) the magnetic flux lines will either tilt to the right or tilt to the left. Where the magnetic flux lines reach the boundary of the magnetically encoded region, the magnetic flux lines from the upper layer will join-up with the magnetic flux lines from the lower layer and visa-versa. This will then form a perfectly controlled toroidal shape.

The benefits of such a magnetic structure are:

- ☐ Reduced (almost eliminated) parasitic magnetic field structures when mechanical stress is applied to the SH (this will result in better RSU performances).
- ☐ Higher Sensor-Output Signal-Slope as there are two "active" layers that compliment each other when generating a mechanical stress related signal. Explanation: When using a single-layer sensor design, the "tilted" magnetic flux lines that exit at the encoding region boundary have to create a "return passage" from one boundary side to the other. This effort effects how much signal is available to be sensed and measured outside of the SH with the secondary sensor unit.
- ☐ There are almost no limitations on the SH (shaft) dimensions where the PCME technology will be applied to. The dual layered magnetic field structure can be adapted to any solid or hollow shaft dimensions.
- ☐ The physical dimensions and sensor performances are in a very wide range programmable and therefore can be tailored to the targeted application.

- This sensor design allows to measure mechanical stresses coming from all three dimensions axis, including in-line forces applied to the shaft (applicable as a load-cell). Explanation: Earlier magnetostriction sensor designs (for example from FAST Technology) have been limited to be sensitive in 2 dimensional axis only, and could not measure in-line forces.

Referring to **Fig.15**, when torque is applied to the SH, the magnetic flux lines from both Counter-Circular magnetic loops are connecting to each other at the sensor region boundaries.

When mechanical torque stress is applied to the SH then the magnetic field will no longer run around in circles but tilt slightly in proportion to the applied torque stress. This will cause the magnetic field lines from one layer to connect to the magnetic field lines in the other layer, and with this form a toroidal shape.

Referring to **Fig.16**, an exaggerated presentation is shown of how the magnetic flux line will form an angled toroidal structure when high levels of torque are applied to the SH.

In the following, features and benefits of the PCM-Encoding (PCME) Process will be described.

The magnetostriction NCT sensing technology from NCTE according to the present invention offers high performance sensing features like:

- No mechanical changes required on the Sensor Host (already existing shafts can be used as they are)

- ☐ Nothing has to be attached to the Sensor Host (therefore nothing can fall off or change over the shaft-lifetime = high MTBF)
- ☐ During measurement the SH can rotate, reciprocate or move at any desired speed (no limitations on rpm)
- ☐ Very good RSU (Rotational Signal Uniformity) performances
- ☐ Excellent measurement linearity (up to 0.01% of FS)
- ☐ High measurement repeatability
- ☐ Very high signal resolution (better than 14 bit)
- ☐ Very high signal bandwidth (better than 10 kHz)

Depending on the chosen type of magnetostriction sensing technology, and the chosen physical sensor design, the mechanical power transmitting shaft (also called "Sensor Host" or in short "SH") can be used "as is" without making any mechanical changes to it or without attaching anything to the shaft. This is then called a "true" Non-Contact-Torque measurement principle allowing the shaft to rotate freely at any desired speed in both directions.

The here described PCM-Encoding (PCME) manufacturing process according to an exemplary embodiment of the present invention provides additional features no other magnetostriction technology can offer (Uniqueness of this technology):

- ☐ More then three times signal strength in comparison to alternative magnetostriction encoding processes (like the "RS" process from FAST).
- ☐ Easy and simple shaft loading process (high manufacturing through-putt).

- No moving components during magnetic encoding process (low complexity manufacturing equipment = high MTBF, and lower cost).
- Process allows NCT sensor to be "fine-tuning" to achieve target accuracy of a fraction of one percent.
- Manufacturing process allows shaft "pre-processing" and "post-processing" in the same process cycle (high manufacturing through-putt).
- Sensing technology and manufacturing process is ratio-metric and therefore is applicable to all shaft or tube diameters.
- The PCM-Encoding process can be applied while the SH is already assembled (depending on accessibility) (maintenance friendly).
- Final sensor is insensitive to axial shaft movements (the actual allowable axial shaft movement depends on the physical "length" of the magnetically encoded region).
- Magnetically encoded SH remains neutral and has little to non magnetic field when no forces (like torque) are applied to the SH.
- Sensitive to mechanical forces in all three dimensional axis.

In the following, the Magnetic Flux Distribution in the SH will be described.

The PCME processing technology is based on using electrical currents, passing through the SH (Sensor Host or Shaft) to achieve the desired, permanent magnetic encoding of the Ferro-magnetic material. To achieve the desired sensor performance and features a very specific and well controlled electrical current is required. Early experiments that used

DC currents failed because of luck of understanding how small amounts and large amounts of DC electric current are travelling through a conductor (in this case the "conductor" is the mechanical power transmitting shaft, also called Sensor Host or in short "SH").

Referring to **Fig.17**, an assumed electrical current density in a conductor is illustrated.

It is widely assumed that the electric current density in a conductor is evenly distributed over the entire cross-section of the conductor when an electric current (DC) passes through the conductor.

Referring to **Fig.18**, a small electrical current forming magnetic field that ties current path in a conductor is shown.

It is our experience that when a small amount of electrical current (DC) is passing through the conductor that the current density is highest at the centre of the conductor. The two main reasons for this are: The electric current passing through a conductor generates a magnetic field that is tying together the current path in the centre of the conductor, and the impedance is the lowest in the centre of the conductor.

Referring to **Fig.19**, a typical flow of small electrical currents in a conductor is illustrated.

In reality, however, the electric current may not flow in a "straight" line from one connection pole to the other (similar to the shape of electric lightening in the sky).

At a certain level of electric current the generated magnetic field is large enough to cause a permanent magnetization of the Ferro-magnetic shaft material. As the electric current is flowing near or at the centre of the SH, the permanently stored magnetic field will reside at the same location: near or at the centre of the SH. When now applying mechanical torque or linear force for oscillation/reciprocation to the shaft, then shaft internally stored magnetic field will respond by tilting its magnetic flux path in accordance to the applied mechanical force. As the permanently stored magnetic field lies deep below the shaft surface the measurable effects are very small, not uniform and therefore not sufficient to build a reliable NCT sensor system.

Referring to **Fig.20**, a uniform current density in a conductor at saturation level is shown.

Only at the saturation level is the electric current density (when applying DC) evenly distributed at the entire cross section of the conductor. The amount of electrical current to achieve this saturation level is extremely high and is mainly influenced by the cross section and conductivity (impedance) of the used conductor.

Referring to **Fig.21**, electric current travelling beneath or at the surface of the conductor (Skin-Effect) is shown.

It is also widely assumed that when passing through alternating current (like a radio frequency signal) through a conductor that the signal is passing through the skin layers of the conductor, called the Skin Effect. The chosen frequency of the alternating current defines the "Location /

position" and "depth" of the Skin Effect. At high frequencies the electrical current will travel right at or near the surface of the conductor (A) while at lower frequencies (in the 5 to 10 Hz regions for a 20 mm diameter SH) the electrical alternating current will penetrate more the centre of the shafts cross section (E). Also, the relative current density is higher in the current occupied regions at higher AC frequencies in comparison to the relative current density near the centre of the shaft at very low AC frequencies (as there is more space available for the current to flow through).

Referring to **Fig.22**, the electrical current density of an electrical conductor (cross-section 90 deg to the current flow) when passing through the conductor an alternating current at different frequencies is illustrated.

The desired magnetic field design of the PCME sensor technology are two circular magnetic field structures, stored in two layers on top of each other ("Picky-Back"), and running in opposite direction to each other (Counter-Circular).

Again referring to **Fig.13**, a desired magnetic sensor structure is shown: two endless magnetic loops placed on top of each other, running in opposite directions to each other: Counter-Circular "Picky-Back" Field Design.

To make this magnetic field design highly sensitive to mechanical stresses that will be applied to the SH (shaft), and to generate the largest sensor signal possible, the desired magnetic field structure has to be placed nearest to the shaft surface. Placing the circular magnetic fields to

close to the centre of the SH will cause damping of the user available sensor-output-signal slope (most of the sensor signal will travel through the Ferro-magnetic shaft material as it has a much higher permeability in comparison to air), and increases the non-uniformity of the sensor signal (in relation to shaft rotation and to axial movements of the shaft in relation to the secondary sensor.

Referring to **Fig.23**, magnetic field structures stored near the shaft surface and stored near the centre of the shaft are illustrated.

It may be difficult to achieve the desired permanent magnetic encoding of the SH when using AC (alternating current) as the polarity of the created magnetic field is constantly changing and therefore may act more as a Degaussing system.

The PCME technology requires that a strong electrical current ("uni-polar" or DC, to prevent erasing of the desired magnetic field structure) is travelling right below the shaft surface (to ensure that the sensor signal will be uniform and measurable at the outside of the shaft). In addition a Counter-Circular, "picky back" magnetic field structure needs to be formed.

It is possible to place the two Counter-Circular magnetic field structures in the shaft by storing them into the shaft one after each other. First the inner layer will be stored in the SH, and then the outer layer by using a weaker magnetic force (preventing that the inner layer will be neutralized and deleted by accident. To achieve this, the known "permanent" magnet encoding techniques can be applied as described in patents from FAST technology, or by using a

combination of electrical current encoding and the "permanent" magnet encoding.

A much simpler and faster encoding process uses "only" electric current to achieve the desired Counter-Circular "Picky-Back" magnetic field structure. The most challenging part here is to generate the Counter-Circular magnetic field.

A uniform electrical current will produce a uniform magnetic field, running around the electrical conductor in a 90 deg angle, in relation to the current direction (A). When placing two conductors side-by-side (B) then the magnetic field between the two conductors seems to cancel-out the effect of each other (C). Although still present, there is no detectable (or measurable) magnetic field between the closely placed two conductors. When placing a number of electrical conductors side-by-side (D) the "measurable" magnetic field seems to go around the outside the surface of the "flat" shaped conductor.

Referring to **Fig.24**, the magnetic effects when looking at the cross-section of a conductor with a uniform current flowing through them are shown.

The "flat" or rectangle shaped conductor has now been bent into a "U"-shape. When passing an electrical current through the "U"-shaped conductor then the magnetic field following the outer dimensions of the "U"-shape is cancelling out the measurable effects in the inner halve of the "U".

Referring to **Fig.25**, the zone inside the "U"-shaped conductor seem to be magnetically "Neutral" when an electrical current is flowing through the conductor.

When no mechanical stress is applied to the cross-section of a "U"-shaped conductor it seems that there is no magnetic field present inside of the "U" (F). But when bending or twisting the "U"-shaped conductor the magnetic field will no longer follow its original path (90 deg angle to the current flow). Depending on the applied mechanical forces, the magnetic field begins to change slightly its path. At that time the magnetic-field-vector that is caused by the mechanical stress can be sensed and measured at the surface of the conductor, inside and outside of the "U"-shape. Note: This phenomena is applies only at very specific electrical current levels.

The same applies to the "O"-shaped conductor design. When passing a uniform electrical current through an "O"-shaped conductor (Tube) the measurable magnetic effects inside of the "O" (Tube) have cancelled-out each other (G).

Referring to **Fig.26**, the zone inside the "O"-shaped conductor seem to be magnetically "Neutral" when an electrical current is flowing through the conductor.

However, when mechanical stresses are applied to the "O"-shaped conductor (Tube) it becomes evident that there has been a magnetic field present at the inner side of the "O"-shaped conductor. The inner, counter directional magnetic field (as well as the outer magnetic field) begins to tilt in relation to the applied torque stresses. This tilting field can be clearly sensed and measured.

In the following, an Encoding Pulse Design will be described.

To achieve the desired magnetic field structure (Counter-Circular, Picky-Back, Fields Design) inside the SH, according to an exemplary embodiment of a method of the present invention, unipolar electrical current pulses are passed through the Shaft (or SH). By using "pulses" the desired "Skin-Effect" can be achieved. By using a "unipolar" current direction (not changing the direction of the electrical current) the generated magnetic effect will not be erased accidentally.

The used current pulse shape is most critical to achieve the desired PCME sensor design. Each parameter has to be accurately and repeatable controlled: Current raising time, Constant current on-time, Maximal current amplitude, and Current falling time. In addition it is very critical that the current enters and exits very uniformly around the entire shaft surface.

In the following, a Rectangle Current Pulse Shape will be described.

Referring to **Fig.27**, a rectangle shaped electrical current pulse is illustrated.

A rectangle shaped current pulse has a fast raising positive edge and a fast falling current edge. When passing a rectangle shaped current pulse through the SH, the raising edge is responsible for forming the targeted magnetic structure of the PCME sensor while the flat "on" time and the falling edge of the rectangle shaped current pulse are counter productive.

Referring to **Fig.28**, a relationship between rectangles shaped Current Encoding Pulse-Width (Constant Current On-Time) and Sensor Output Signal Slope is shown.

In the following example a rectangle shaped current pulse has been used to generate and store the Couter-Circilar "Picky-Back" field in a 15 mm diameter, 14CrNi14 shaft. The pulsed electric current had its maximum at around 270 Ampere. The pulse "on-time" has been electronically controlled. Because of the high frequency component in the rising and falling edge of the encoding pulse, this experiment can not truly represent the effects of a true DC encoding SH. Therefore the Sensor-Output-Signal Slope-curve eventually flattens-out at above 20 mV/Nm when passing the Constant-Current On-Time of 1000 ms.

Without using a fast raising current-pulse edge (like using a controlled ramping slope) the sensor output signal slope would have been very poor (below 10 mV/Nm). Note: In this experiment (using 14CrNi14) the signal hysteresis was around 0.95% of the FS signal (FS = 75 Nm torque).

Referring to **Fig.29**, increasing the Sensor-Output Signal-Slope by using several rectangle shaped current pulses in succession is shown.

The Sensor-Output-Signal slope can be improved when using several rectangle shaped current-encoding-pulses in successions. In comparisons to other encoding-pulse-shapes the fast falling current-pulse signal slope of the rectangle shaped current pulse will prevent that the Sensor-Output-Signal slope may ever reach an optimal performance level. Meaning that after only a few current pulses (2 to 10) have

been applied to the SH (or Shaft) the Sensor-Output Signal-Slope will no longer rise.

In the following, a Discharge Current Pulse Shape is described.

The Discharge-Current-Pulse has no Constant-Current ON-Time and has no fast falling edge. Therefore the primary and most felt effect in the magnetic encoding of the SH is the fast raising edge of this current pulse type.

As shown in **Fig.30**, a sharp raising current edge and a typical discharging curve provides best results when creating a PCME sensor.

Referring to **Fig.31**, a PCME Sensor-Output Signal-Slope optimization by identifying the right pulse current is illustrated.

At the very low end of the pulse current scale (0 to 75 A for a 15 mm diameter shaft, 14CrNi14 shaft material) the "Discharge-Current-Pulse type is not powerful enough to cross the magnetic threshold needed to create a lasting magnetic field inside the Ferro magnetic shaft. When increasing the pulse current amplitude the double circular magnetic field structure begins to form below the shaft surface. As the pulse current amplitude increases so does the achievable torque sensor-output signal-amplitude of the secondary sensor system. At around 400A to 425A the optimal PCME sensor design has been achieved (the two counter flowing magnetic regions have reached their most optimal distance to each other and the correct flux density for best sensor performances.

Referring to **Fig.32**, Sensor Host (SH) cross section with the optimal PCME electrical current density and location during the encoding pulse is illustrated.

When increasing further the pulse current amplitude the absolute, torque force related, sensor signal amplitude will further increase (curve 2) for some time while the overall PCME-typical sensor performances will decrease (curve 1). When passing 900A Pulse Current Amplitude (for a 15 mm diameter shaft) the absolute, torque force related, sensor signal amplitude will begin to drop as well (curve 2) while the PCME sensor performances are now very poor (curve 1).

Referring to **Fig.33**, Sensor Host (SH) cross sections and the electrical pulse current density at different and increasing pulse current levels is shown.

As the electrical current occupies a larger cross section in the SH the spacing between the inner circular region and the outer (near the shaft surface) circular region becomes larger.

Referring to **Fig.34**, better PCME sensor performances will be achieved when the spacing between the Counter-Circular "Picky-Back" Field design is narrow (A).

The desired double, counter flow, circular magnetic field structure will be less able to create a close loop structure under torque forces which results in a decreasing secondary sensor signal amplitude.

Referring to **Fig.35**, flattening-out the current-discharge curve will also increase the Sensor-Output Signal-Slope.

When increasing the Current-Pulse discharge time (making the current pulse wider) (B) the Sensor-Output Signal-Slope will increase. However the required amount of current is very high to reduce the slope of the falling edge of the current pulse. It might be more practical to use a combination of a high current amplitude (with the optimal value) and the slowest possible discharge time to achieve the highest possible Sensor-Output Signal Slope.

In the following, Electrical Connection Devices in the frame of Primary Sensor Processing will be described.

The PCME technology (it has to be noted that the term 'PCME' technology is used to refer to exemplary embodiments of the present invention) relies on passing through the shaft very high amounts of pulse-modulated electrical current at the location where the Primary Sensor should be produced. When the surface of the shaft is very clean and highly conductive a multi-point Cupper or Gold connection may be sufficient to achieve the desired sensor signal uniformity. Important is that the Impedance is identical of each connection point to the shaft surface. This can be best achieved when assuring the cable length (L) is identical before it joins the main current connection point (I).

Referring to **Fig.36**, a simple electrical multi-point connection to the shaft surface is illustrated.

However, in most cases a reliable and repeatable multi-point electrical connection can be only achieved by ensuring that the impedance at each connection point is identical and constant. Using a spring pushed, sharpened connector will

penetrate possible oxidation or isolation layers (maybe caused by finger prints) at the shaft surface.

Referring to **Fig.37**, a multi channel, electrical connecting fixture, with spring loaded contact points is illustrated.

When processing the shaft it is most important that the electrical current is injected and extracted from the shaft in the most uniform way possible. The above drawing shows several electrical, from each other insulated, connectors that are held by a fixture around the shaft. This device is called a Shaft-Processing-Holding-Clamp (or SPHC). The number of electrical connectors required in a SPHC depends on the shafts outer diameter. The larger the outer diameter, the more connectors are required. The spacing between the electrical conductors has to be identical from one connecting point to the next connecting point. This method is called Symmetrical-"Spot"-Contacts.

Referring to **Fig.38**, it is illustrated that increasing the number of electrical connection points will assist the efforts of entering and exiting the Pulse-Modulated electrical current. It will also increase the complexity of the required electronic control system.

Referring to **Fig.39**, an example of how to open the SPHC for easy shaft loading is shown.

In the following, an encoding scheme in the frame of Primary Sensor Processing will be described.

The encoding of the primary shaft can be done by using permanent magnets applied at a rotating shaft or using

electric currents passing through the desired section of the shaft. When using permanent magnets a very complex, sequential procedure is necessary to put the two layers of closed loop magnetic fields, on top of each other, in the shaft. When using the PCME procedure the electric current has to enter the shaft and exit the shaft in the most symmetrical way possible to achieve the desired performances.

Referring to **Fig.40**, two SPHCs (Shaft Processing Holding Clamps) are placed at the borders of the planned sensing encoding region. Through one SPHC the pulsed electrical current (I) will enter the shaft, while at the second SPHC the pulsed electrical current (I) will exit the shaft. The region between the two SPHCs will then turn into the primary sensor.

This particular sensor process will produce a Single Field (SF) encoded region. One benefit of this design (in comparison to those that are described below) is that this design is insensitive to any axial shaft movements in relation to the location of the secondary sensor devices. The disadvantage of this design is that when using axial (or in-line) placed MFS coils the system will be sensitive to magnetic stray fields (like the earth magnetic field).

Referring to **Fig.41**, a Dual Field (DF) encoded region (meaning two independent functioning sensor regions with opposite polarity, side-by-side) allows cancelling the effects of uniform magnetic stray fields when using axial (or in-line) placed MFS coils. However, this primary sensor design also shortens the tolerable range of shaft movement in axial direction (in relation to the location of the MFS coils). There are two ways to produce a Dual Field (DF)

encoded region with the PCME technology. The sequential process, where the magnetic encoded sections are produced one after each other, and the parallel process, where both magnetic encoded sections are produced at the same time.

The first process step of the sequential dual field design is to magnetically encode one sensor section (identically to the Single Field procedure), whereby the spacing between the two SPHC has to be halve of the desired final length of the Primary Sensor region. To simplify the explanations of this process we call the SPHC that is placed in the centre of the final Primary Sensor Region the Centre SPHC (C-SPHC), and the SPHC that is located at the left side of the Centre SPHC: L-SPHC.

Referring to **Fig.42**, the second process step of the sequential Dual Field encoding will use the SPHC that is located in the centre of the Primary Sensor region (called C-SPHC) and a second SPHC that is placed at the other side (the right side) of the centre SPHC, called R-SPHC. Important is that the current flow direction in the centre SPHC (C-SPHC) is identical at both process steps.

Referring to **Fig.43**, the performance of the final Primary Sensor Region depends on how close the two encoded regions can be placed in relation to each other. And this is dependent on the design of the used centre SPHC. The narrower the in-line space contact dimensions are of the C-SPHC, the better are the performances of the Dual Field PCME sensor.

Fig.44 shows the pulse application according to another exemplary embodiment of the present invention. As my be taken from the above drawing, the pulse is applied to three

locations of the shaft. Due to the current distribution to both sides of the middle electrode where the current I is entered into the shaft, the current leaving the shaft at the lateral electrodes is only half the current entered at the middle electrode, namely ½ I. The electrodes are depicted as rings which dimensions are adapted to the dimensions of the outer surface of the shaft. However, it has to be noted that other electrodes may be used, such as the electrodes comprising a plurality of pin electrodes described later in this text.

Referring to **Fig.45**, magnetic flux directions of the two sensor sections of a Dual Field PCME sensor design are shown when no torque or linear motion stress is applied to the shaft. The counter flow magnetic flux loops do not interact with each other.

Referring to **Fig.46**, when torque forces or linear stress forces are applied in a particular direction then the magnetic flux loops begin to run with an increasing tilting angle inside the shaft. When the tilted magnetic flux reaches the PCME segment boundary then the flux line interacts with the counterflowing magnetic flux lines, as shown.

Referring to **Fig.47**, when the applied torque direction is changing (for example from clock-wise to counter-clock-wise) so will change the tilting angle of the counterflow magnetic flux structures inside the PCM Encoded shaft.

In the following, a Multi Channel Current Driver for Shaft Processing will be described.

In cases where an absolute identical impedance of the current path to the shaft surface can not be guaranteed, then electric current controlled driver stages can be used to overcome this problem.

Referring to **Fig.48**, a six-channel synchronized Pulse current driver system for small diameter Sensor Hosts (SH) is shown. As the shaft diameter increases so will the number of current driver channels.

In the following, Bras Ring Contacts and Symmetrical "Spot" Contacts will be described.

When the shaft diameter is relative small and the shaft surface is clean and free from any oxidations at the desired Sensing Region, then a simple "Bras"-ring (or Copper-ring) contact method can be chosen to process the Primary Sensor.

Referring to **Fig.49**, bras-rings (or Copper-rings) tightly fitted to the shaft surface may be used, with solder connections for the electrical wires. The area between the two Bras-rings (Copper-rings) is the encoded region.

However, it is very likely that the achievable RSU performances are much lower then when using the Symmetrical "Spot" Contact method.

In the following, a Hot-Spotting concept will be described.

A standard single field (SF) PCME sensor has very poor Hot-Spotting performances. The external magnetic flux profile of the SF PCME sensor segment (when torque is applied) is very sensitive to possible changes (in relation to Ferro magnetic

material) in the nearby environment. As the magnetic boundaries of the SF encoded sensor segment are not well defined (not "Pinned Down") they can "extend" towards the direction where Ferro magnet material is placed near the PCME sensing region.

Referring to **Fig.50**, a PCME process magnetized sensing region is very sensitive to Ferro magnetic materials that may come close to the boundaries of the sensing regions.

To reduce the Hot-Spotting sensor sensitivity the PCME sensor segment boundaries have to be better defined by pinning them down (they can no longer move).

Referring to **Fig.51**, a PCME processed Sensing region with two "Pinning Field Regions" is shown, one on each side of the Sensing Region.

By placing Pinning Regions closely on either side the Sensing Region, the Sensing Region Boundary has been pinned down to a very specific location. When Ferro magnetic material is coming close to the Sensing Region, it may have an effect on the outer boundaries of the Pinning Regions, but it will have very limited effects on the Sensing Region Boundaries.

There are a number of different ways, according to exemplary embodiments of the present invention how the SH (Sensor Host) can be processed to get a Single Field (SF) Sensing Region and two Pinning Regions, one on each side of the Sensing Region. Either each region is processed after each other (Sequential Processing) or two or three regions are processed simultaneously (Parallel Processing). The Parallel Processing provides a more uniform sensor (reduced parasitic fields) but

requires much higher levels of electrical current to get to the targeted sensor signal slope.

Referring to **Fig.52**, a parallel processing example for a Single Field (SF) PCME sensor with Pinning Regions on either side of the main sensing region is illustrated, in order to reduce (or even eliminate) Hot-Spotting.

A Dual Field PCME Sensor is less sensitive to the effects of Hot-Spotting as the sensor centre region is already Pinned-Down. However, the remaining Hot-Spotting sensitivity can be further reduced by placing Pinning Regions on either side of the Dual-Field Sensor Region.

Referring to **Fig.53**, a Dual Field (DF) PCME sensor with Pinning Regions either side is shown.

When Pinning Regions are not allowed or possible (example: limited axial spacing available) then the Sensing Region has to be magnetically shielded from the influences of external Ferro Magnetic Materials.

In the following, the Rotational Signal Uniformity (RSU) will be explained.

The RSU sensor performance are, according to current understanding, mainly depending on how circumferentially uniform the electrical current entered and exited the SH surface, and the physical space between the electrical current entry and exit points. The larger the spacing between the current entry and exit points, the better is the RSU performance.

Referring to **Fig.54**, when the spacings between the individual circumferential placed current entry points are relatively large in relation to the shaft diameter (and equally large are the spacings between the circumferentially placed current exit points) then this will result in very poor RSU performances. In such a case the length of the PCM Encoding Segment has to be as large as possible as otherwise the created magnetic field will be circumferentially non-uniform.

Referring to **Fig.55**, by widening the PCM Encoding Segment the circumferentially magnetic field distribution will become more uniform (and eventually almost perfect) at the halve distance between the current entry and current exit points. Therefore the RSU performance of the PCME sensor is best at the halve way-point between of the current-entry / current-exit points.

Next, the basic design issues of a NCT sensor system will be described.

Without going into the specific details of the PCM-Encoding technology, the end-user of this sensing technology need to now some design details that will allow him to apply and to use this sensing concept in his application. The following pages describe the basic elements of a magnetostriction based NCT sensor (like the primary sensor, secondary sensor, and the SCSP electronics), what the individual components look like, and what choices need to be made when integrating this technology into an already existing product.

In principle the PCME sensing technology can be used to produce a stand-alone sensor product. However, in already

existing industrial applications there is little to none space available for a "stand-alone" product. The PCME technology can be applied in an existing product without the need of redesigning the final product.

In case a stand-alone torque sensor device or position detecting sensor device will be applied to a motor-transmission system it may require that the entire system need to undergo a major design change.

In the following, referring to Fig.56, a possible location of a PCME sensor at the shaft of an engine is illustrated.

Next, Sensor Components will be explained.

A non-contact magnetostriction sensor (NCT-Sensor), as shown in **Fig.57**, may consist, according to an exemplary embodiment of the present invention, of three main functional elements: The Primary Sensor, the Secondary Sensor, and the Signal Conditioning & Signal Processing (SCSP) electronics.

Depending on the application type (volume and quality demands, targeted manufacturing cost, manufacturing process flow) the customer can chose to purchase either the individual components to build the sensor system under his own management, or can subcontract the production of the individual modules.

Fig.58 shows a schematic illustration of components of a non-contact torque sensing device. However, these components can also be implemented in a non-contact position sensing device.

In cases where the annual production target is in the thousands of units it may be more efficient to integrate the "primary-sensor magnetic-encoding-process" into the customers manufacturing process. In such a case the customer needs to purchase application specific "magnetic encoding equipment".

In high volume applications, where cost and the integrity of the manufacturing process are critical, it is typical that NCTE supplies only the individual basic components and equipment necessary to build a non-contact sensor:

- ☐ ICs (surface mount packaged, Application-Specific Electronic Circuits)
- ☐ MFS-Coils (as part of the Secondary Sensor)
- ☐ Sensor Host Encoding Equipment (to apply the magnetic encoding on the shaft = Primary Sensor)

Depending on the required volume, the MFS-Coils can be supplied already assembled on a frame, and if desired, electrically attached to a wire harness with connector. Equally the SCSP (Signal Conditioning & Signal Processing) electronics can be supplied fully functional in PCB format, with or without the MFS-Coils embedded in the PCB.

Fig.59 shows components of a sensing device.

As can be seen from **Fig.60**, the number of required MFS-coils is dependent on the expected sensor performance and the mechanical tolerances of the physical sensor design. In a well designed sensor system with perfect Sensor Host (SH or magnetically encoded shaft) and minimal interferences from unwanted magnetic stray fields, only 2 MFS-coils are needed. However, if the SH is moving radial or axial in relation to

the secondary sensor position by more than a few tenths of a millimeter, then the number of MFS-coils need to be increased to achieve the desired sensor performance.

In the following, a control and/or evaluation circuitry will be explained.

The SCSP electronics, according to an exemplary embodiment of the present invention, consist of the NCTE specific ICs, a number of external passive and active electronic circuits, the printed circuit board (PCB), and the SCSP housing or casing. Depending on the environment where the SCSP unit will be used the casing has to be sealed appropriately.

Depending on the application specific requirements NCTE (according to an exemplary embodiment of the present invention) offers a number of different application specific circuits:

- ☐ Basic Circuit
- ☐ Basic Circuit with integrated Voltage Regulator
- ☐ High Signal Bandwidth Circuit
- ☐ Optional High Voltage and Short Circuit Protection Device
- ☐ Optional Fault Detection Circuit

Fig.61 shows a single channel, low cost sensor electronics solution.

Fig.62 shows a dual channel, short circuit protected system design with integrated fault detection. This design consists of 5 ASIC devices and provides a high degree of system safety. The Fault-Detection IC identifies when there is a

wire breakage anywhere in the sensor system, a fault with the MFS coils, or a fault in the electronic driver stages of the "Basic IC".

Next, the Secondary Sensor Unit will be explained.

The Secondary Sensor may, according to one embodiment shown in **Fig.63**, consist of the elements: One to eight MFS (Magnetic Field Sensor) Coils, the Alignment - & Connection-Plate, the wire harness with connector, and the Secondary-Sensor-Housing.

The MFS-coils may be mounted onto the Alignment-Plate. Usually the Alignment-Plate allows that the two connection wires of each MFS-Coil are soldered / connected in the appropriate way. The wire harness is connected to the alignment plate. This, completely assembled with the MFS-Coils and wire harness, is then embedded or held by the Secondary-Sensor-Housing.

The main element of the MFS-Coil is the core wire, which has to be made out of an amorphous-like material.

Depending on the environment where the Secondary-Sensor-Unit will be used, the assembled Alignment Plate has to be covered by protective material. This material can not cause mechanical stress or pressure on the MFS-coils when the ambient temperature is changing.

In applications where the operating temperature will not exceed +110 deg C the customer has the option to place the SCSP electronics (ASIC) inside the secondary sensor unit

(SSU). While the ASIC devices can operated at temperatures above +125 deg C it will become increasingly more difficult to compensate the temperature related signal-offset and signal-gain changes.

The recommended maximal cable length between the MFS-coils and the SCSP electronics is 2 meters. When using the appropriate connecting cable, distances of up to 10 meters are achievable. To avoid signal-cross-talk in multi-channel applications (two independent SSUs operating at the same Primary Sensor location = Redundant Sensor Function), specially shielded cable between the SSUs and the SCSP Electronics should be considered.

When planning to produce the Secondary-Sensor-Unit (SSU) the producer has to decide which part / parts of the SSU have to be purchased through subcontracting and which manufacturing steps will be made in-house.

In the following, Secondary Sensor Unit Manufacturing Options will be described.

When integrating the NCT-Sensor into a customized tool or standard transmission system then the systems manufacturer has several options to choose from:

- ☐ custom made SSU (including the wire harness and connector)
- ☐ selected modules or components; the final SSU assembly and system test may be done under the customer's management.

- only the essential components (MFS-coils or MFS-core-wire, Application specific ICs) and will produce the SSU in-house.

Fig.64 illustrates an exemplary embodiment of a Secondary Sensor Unit Assembly.

Next, a Primary Sensor Design is explained.

The SSU (Secondary Sensor Units) can be placed outside the magnetically encoded SH (Sensor Host) or, in case the SH is hollow, inside the SH. The achievable sensor signal amplitude is of equal strength but has a much better signal-to-noise performance when placed inside the hollow shaft.

Fig.65 illustrates two configurations of the geometrical arrangement of Primary Sensor and Secondary Sensor.

Improved sensor performances may be achieved when the magnetic encoding process is applied to a straight and parallel section of the SH (shaft). For a shaft with 15 mm to 25 mm diameter the optimal minimum length of the Magnetically Encoded Region is 25 mm. The sensor performances will further improve if the region can be made as long as 45 mm (adding Guard Regions). In complex and highly integrated transmission (gearbox) systems it will be difficult to find such space. Under more ideal circumstances, the Magnetically Encoding Region can be as short as 14 mm, but this bears the risk that not all of the desired sensor performances can be achieved.

As illustrated in **Fig.66**, the spacing between the SSU (Secondary Sensor Unit) and the Sensor Host surface, according to an exemplary embodiment of the present

invention, should be held as small as possible to achieve the best possible signal quality.

Next, the Primary Sensor Encoding Equipment will be described.

An example is shown in **Fig.67**.

Depending on which magnetostriction sensing technology will be chosen, the Sensor Host (SH) needs to be processed and treated accordingly. The technologies vary by a great deal from each other (ABB, FAST, FT, Kubota, MDI, NCTE, RM, Siemens, …) and so does the processing equipment required. Some of the available magnetostriction sensing technologies do not need any physical changes to be made on the SH and rely only on magnetic processing (MDI, FAST, NCTE).

While the MDI technology is a two phase process, the FAST technology is a three phase process, and the NCTE technology a one phase process, called PCM Encoding.

One should be aware that after the magnetic processing, the Sensor Host (SH or Shaft), has become a "precision measurement" device and has to be treated accordingly. The magnetic processing should be the very last step before the treated SH is carefully placed in its final location.

The magnetic processing should be an integral part of the customer's production process (in-house magnetic processing) under the following circumstances:

- ☐ High production quantities (like in the thousands)

- ☐ Heavy or difficult to handle SH (e.g. high shipping costs)
- ☐ Very specific quality and inspection demands (e.g. defense applications)

In all other cases it may be more cost effective to get the SH magnetically treated by a qualified and authorized subcontractor, such as NCTE. For the "in-house" magnetic processing dedicated manufacturing equipment is required. Such equipment can be operated fully manually, semi-automated, and fully automated. Depending on the complexity and automation level the equipment can cost anywhere from EUR 20k to above EUR 500k.

It should be noted that the term "comprising" does not exclude other elements or steps and the "a" or "an" does not exclude a plurality. Also elements described in association with different embodiments may be combined.

What Is claimed is:

An array for adjusting a magnetization of a magnetizable object, comprising:

an object having a magnetized portion extending along at least a part of the object;

at least one degaussing element arranged adjacent to the magnetized portion, the at least one degaussing element being adapted to be activated to degauss a part of the magnetized portion to adjust the magnetization of the magnetizable object by forming a demagnetized portion of the object directly adjacent to a remaining magnetized portion of the object;

wherein the object is a shaft;

wherein the shaft has a first unmagnetized portion and a second unmagnetized portion, the magnetized portion being arranged between the first unmagnetized portion and the second unmagnetized portion;

having a first degaussing coil and having a second degaussing coil as degaussing elements, the first degaussing coil being arranged surrounding a portion of the magnetized portion adjacent the first unmagnetized portion, and the second degaussing coil being arranged surrounding a portion of the magnetized portion adjacent the second unmagnetized portion;

wherein the first degaussing coil has a first connection and a second connection, and wherein the second degaussing coil has a first connection and a second connection, wherein a first voltage is applyable between the first connection and the second connection of the first degaussing coil, and a second voltage is applyable between the first connection and the second connection of the second degaussing coil;

having a first stopper coil and having a second stopper

coil, the first stopper coil being arranged surrounding a portion of the magnetized portion adjacent the first degaussing coil, and the second stopper coil being arranged surrounding a portion of the magnetized portion adjacent the second degaussing coil in such a manner that the first and second stopper coils are arranged between the first and second degaussing coils, wherein such an electrical signal can be applied to the first and second the stopper coils that a region between the first and second stopper coils is prevented from being demagnetized when the degaussing elements are magnetized;

wherein the magnetized portion is a circumferentially magnetized region of the reciprocating object.

N 7178

Abstract

A method and an array for adjusting a magnetization of a magnetizable object, and the use of at least one activatable degaussing element to degauss a part of a magnetized portion of an object

A method for adjusting a magnetization of a magnetizable object, the method comprising the steps of providing an object having a magnetized portion extending along at least a part of the object, arranging at least one degaussing element adjacent to the magnetized portion, and degaussing a part of the magnetized portion by activating the degaussing element to adjust the magnetization of the magnetizable object by forming a demagnetized portion of the object directly adjacent to a remaining magnetized portion of the object. (Fig.10)

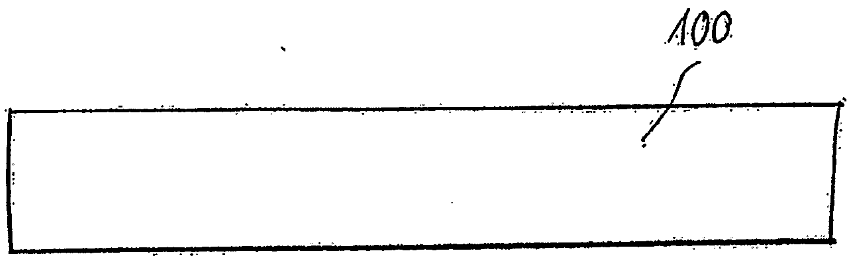

Fig. 1

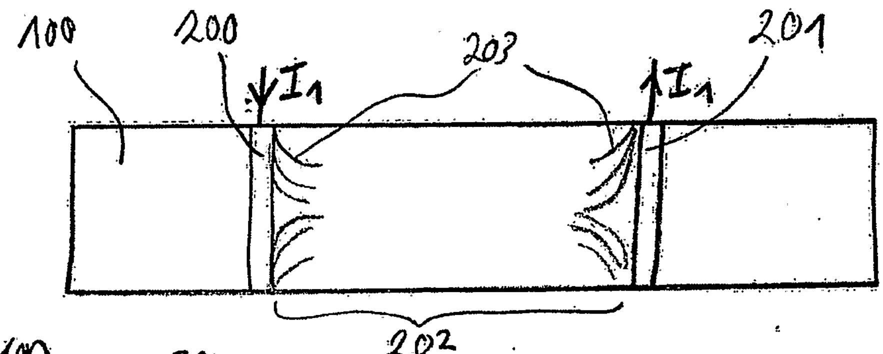

Fig. 2

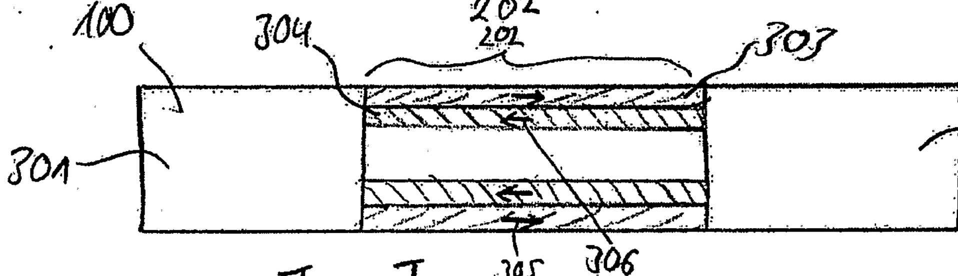

Fig. 3

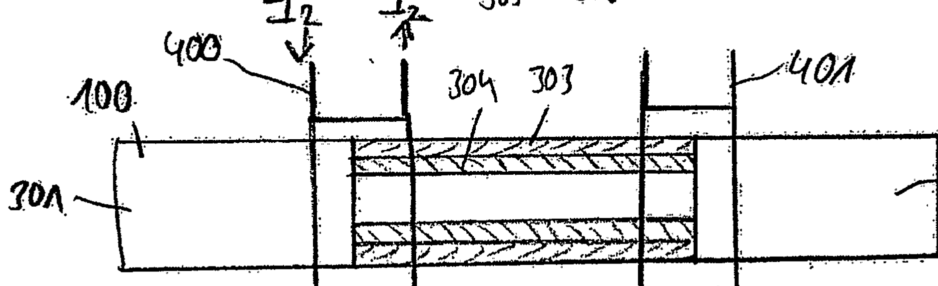

Fig. 4

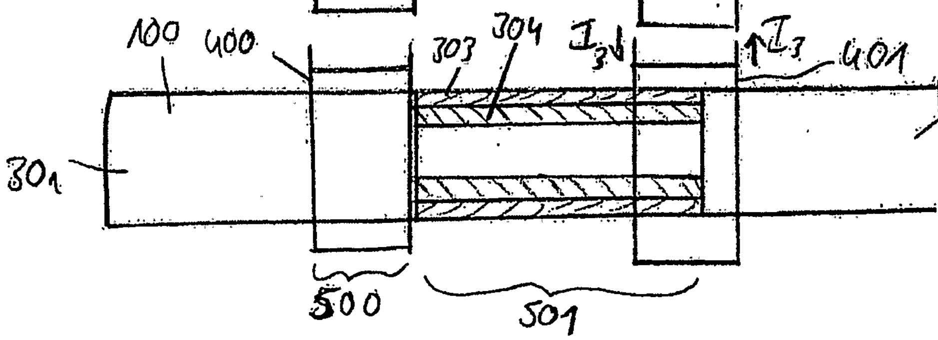

Fig. 5

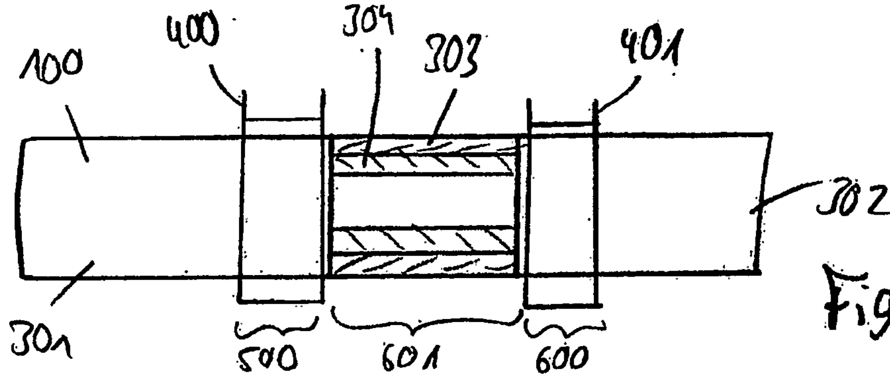

Fig. 6

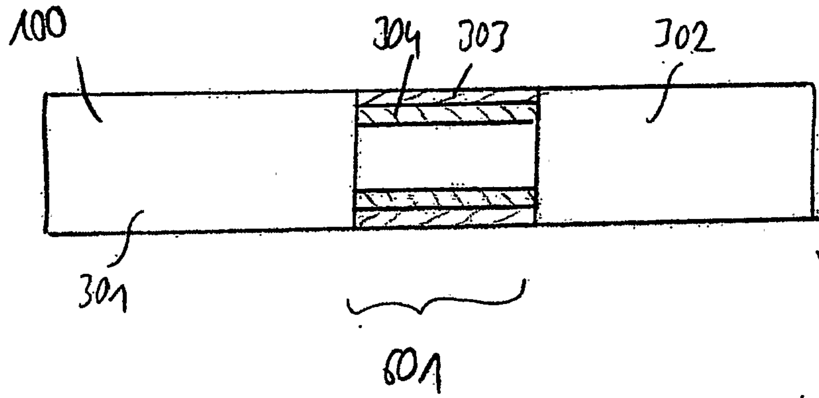

Fig. 7

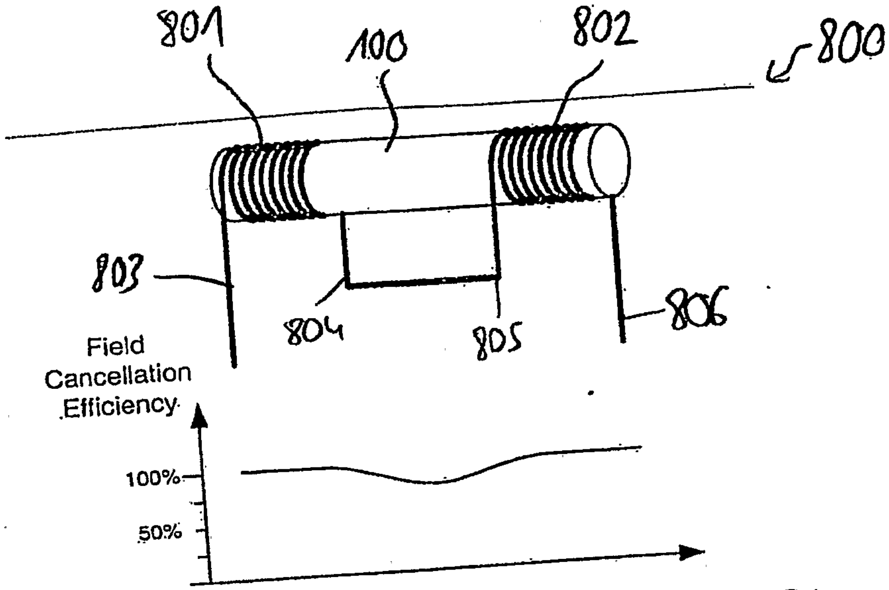
801
100
802
800
803
804
805
806
Field Cancellation Efficiency
100%
50%

Fig. 8

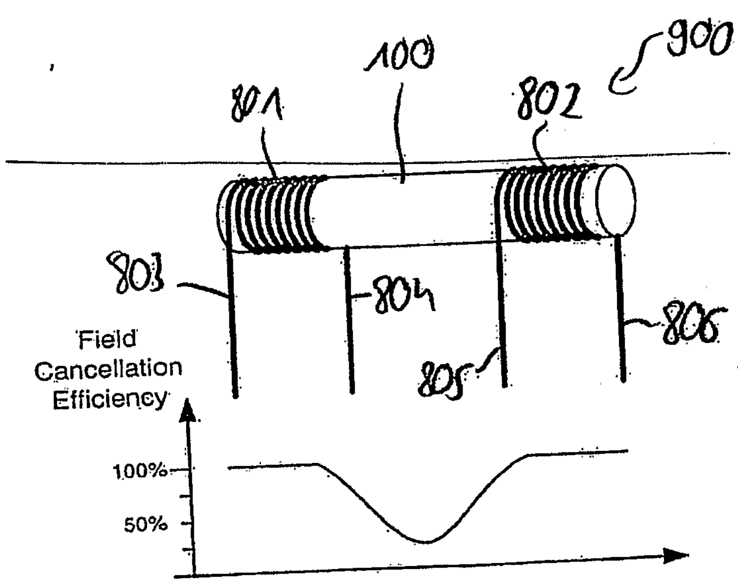
100
900
801
802
803
804
806
805
Field Cancellation Efficiency
100%
50%

Fig. 9

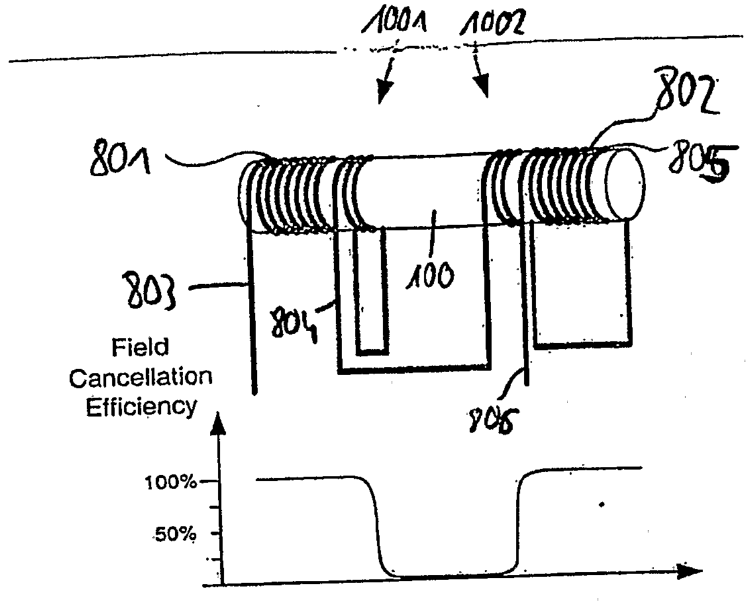

Fig. 10A

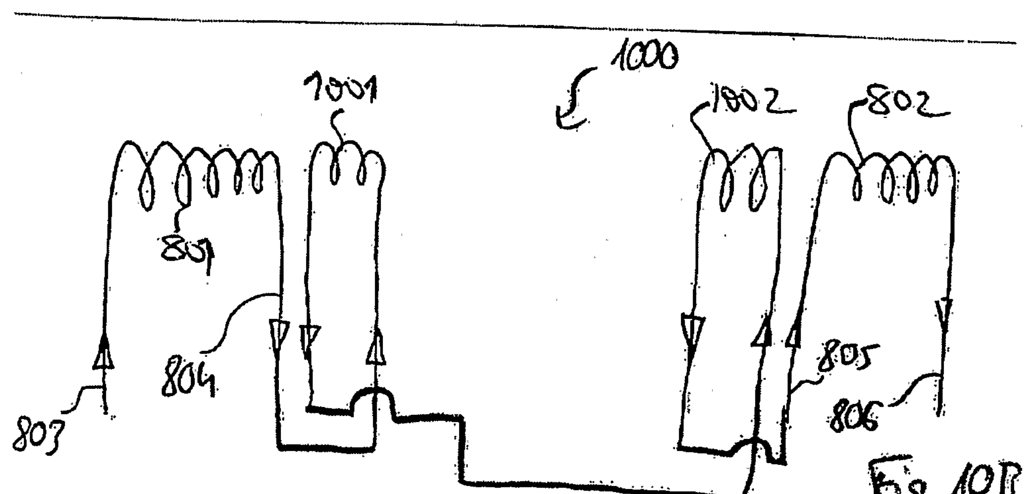

Fig. 10B

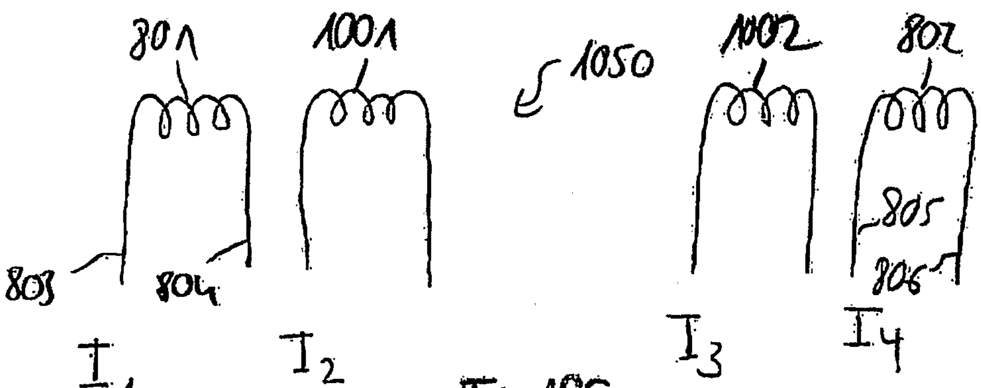

Fig. 10C

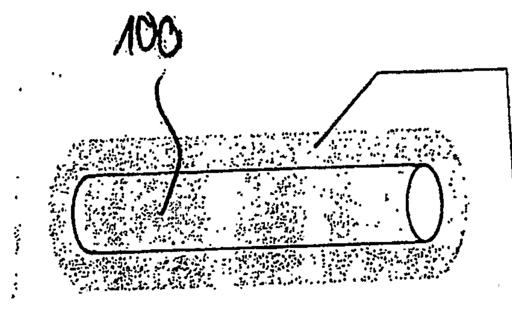

Fig. 11A

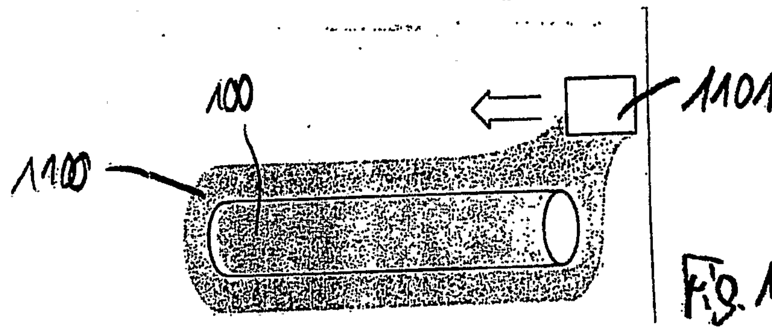

Fig. 11B

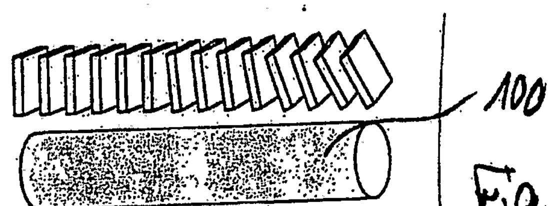

Fig. 11C

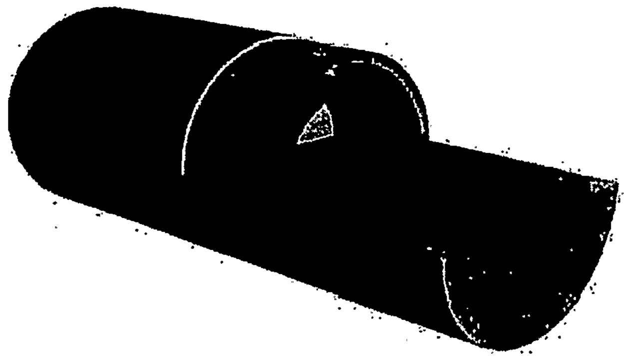

Fig. 12

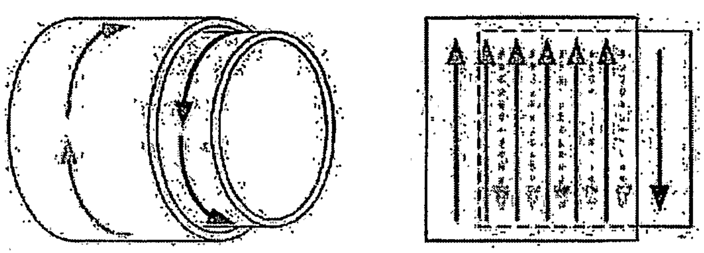

Fig. 13

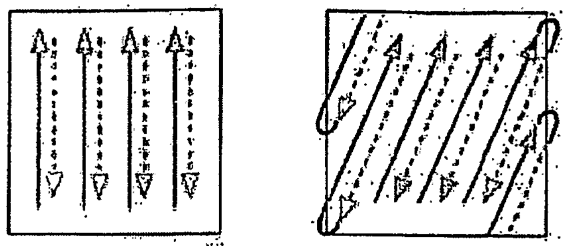

Fig. 14

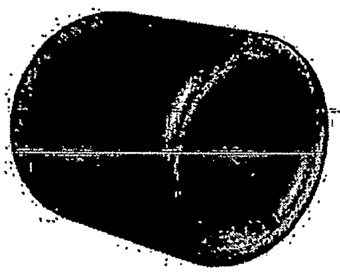

Fig. 15

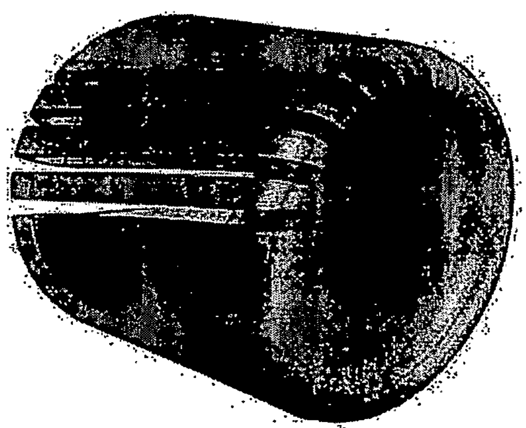

Fig. 16

Fig. 17

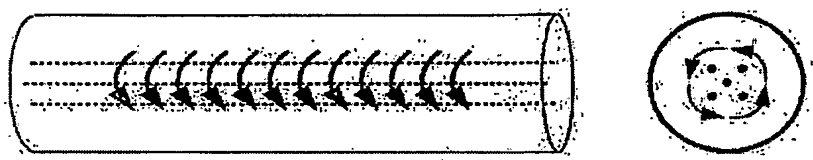

Fig. 18

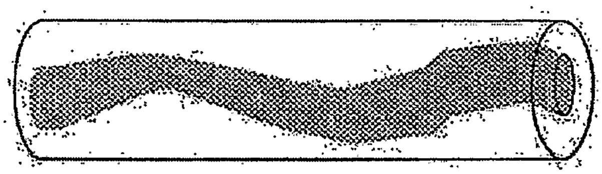

Fig. 19

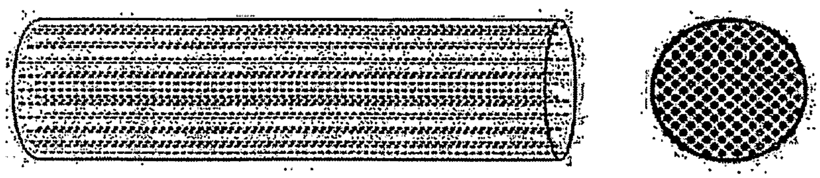

Fig. 20

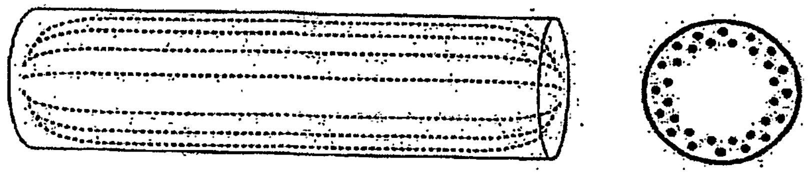

Fig. 21

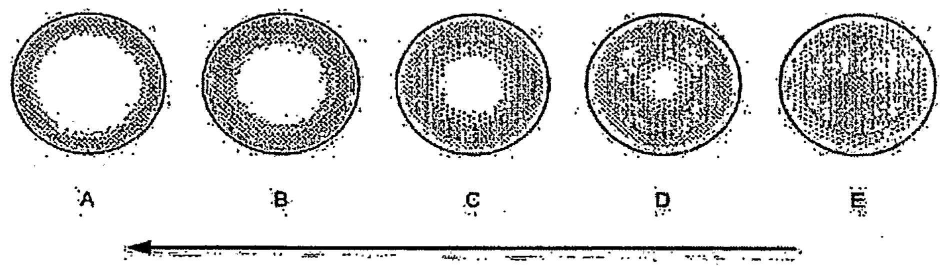

Fig. 22

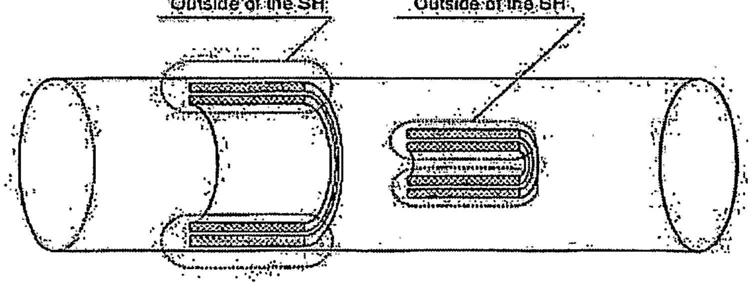

Fig. 23

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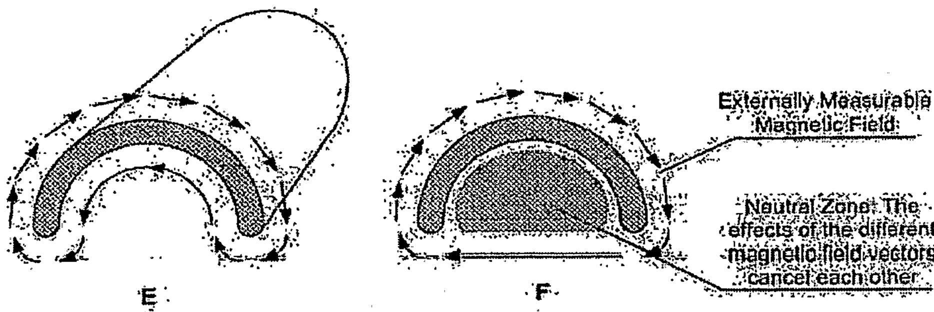
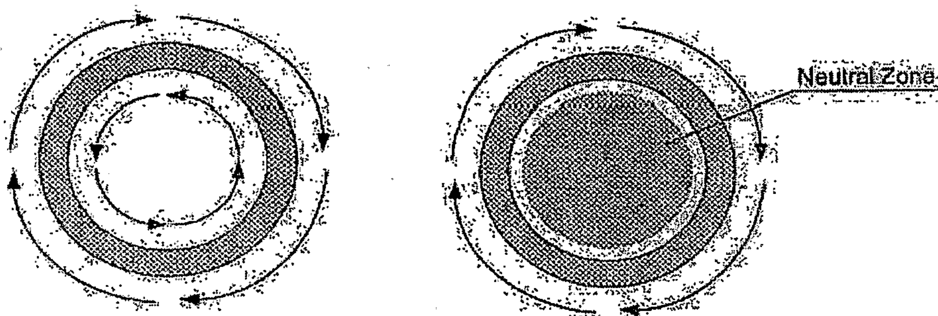
A B C D

Fig. 24



E F

Fig. 25



G H

Fig. 26

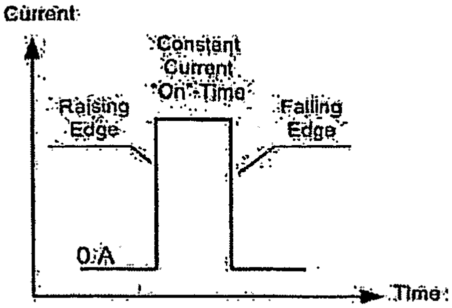

Current
Constant Current On Time
Raising Edge
Falling Edge
0 A
Time

Fig. 27

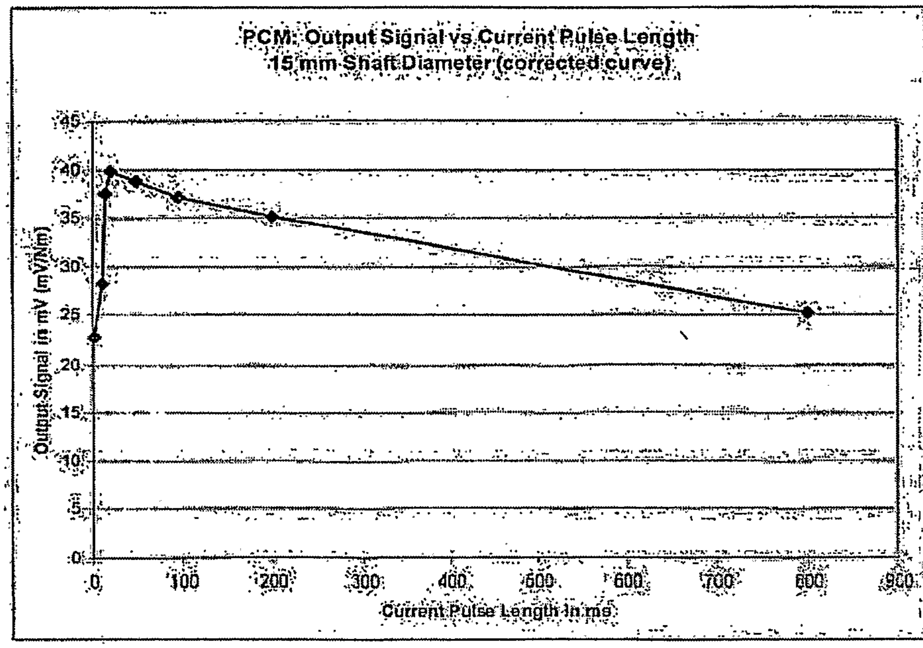

PCM: Output Signal vs Current Pulse Length
15 mm Shaft Diameter (corrected curve)
Output Signal in mV (mV/Nm)
45
40
35
30
25
20
15
10
5
0
0
100
200
300
400
500
600
700
800
900
Current Pulse Length in ms

Fig. 28

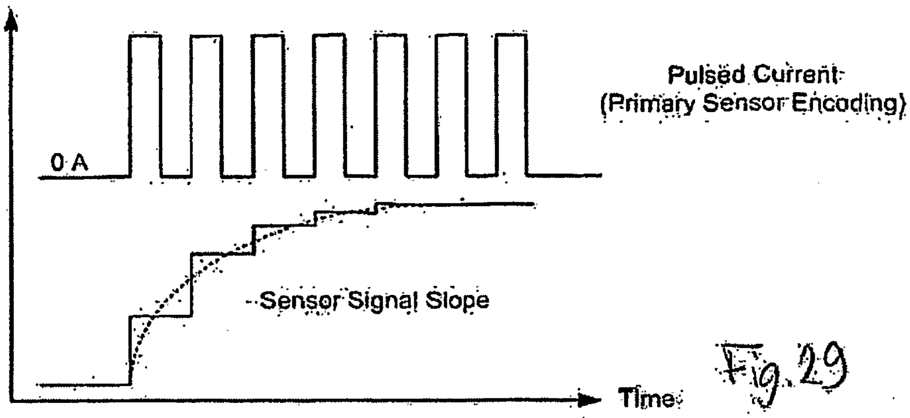


Fig. 29

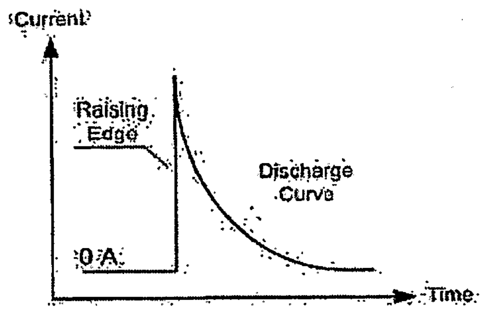


Fig 30

Signal (mV/Nm) and Signal Efficiency (µV/(Nm*A)) vs Current at 15mm Shaft

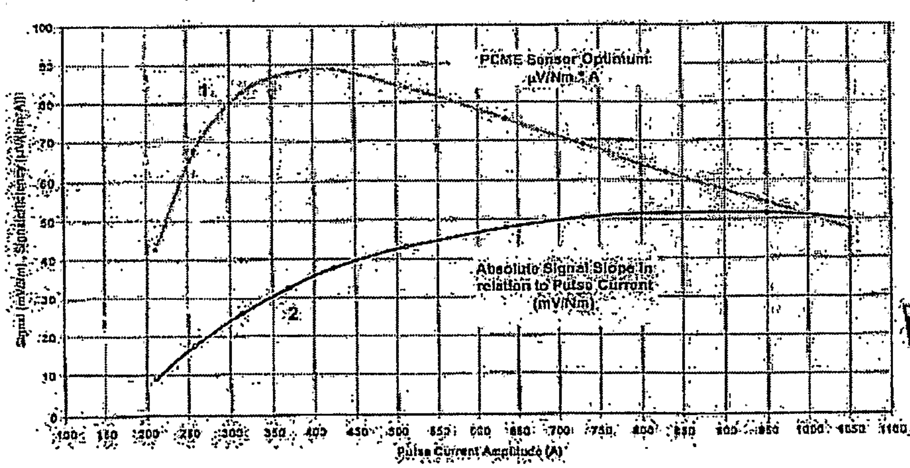


Fig 31

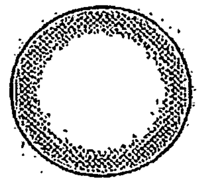


Fig. 32

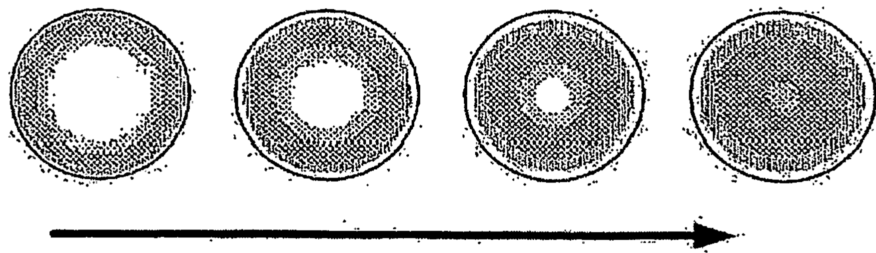


Fig. 33

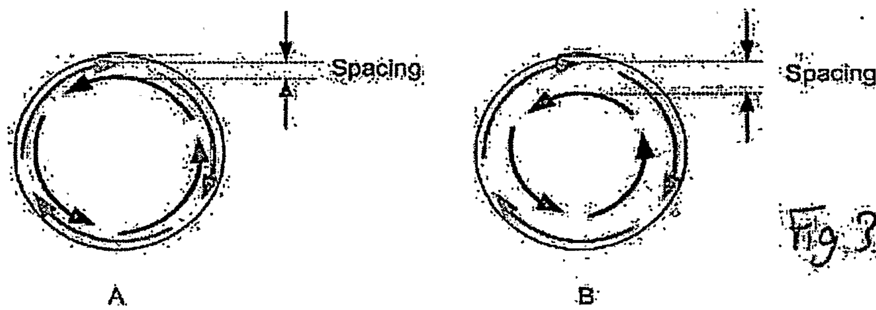


Fig. 34

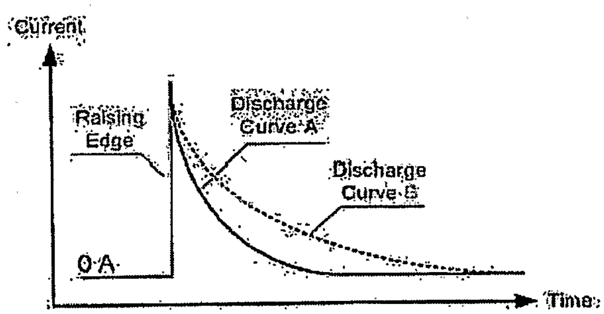


Fig. 35

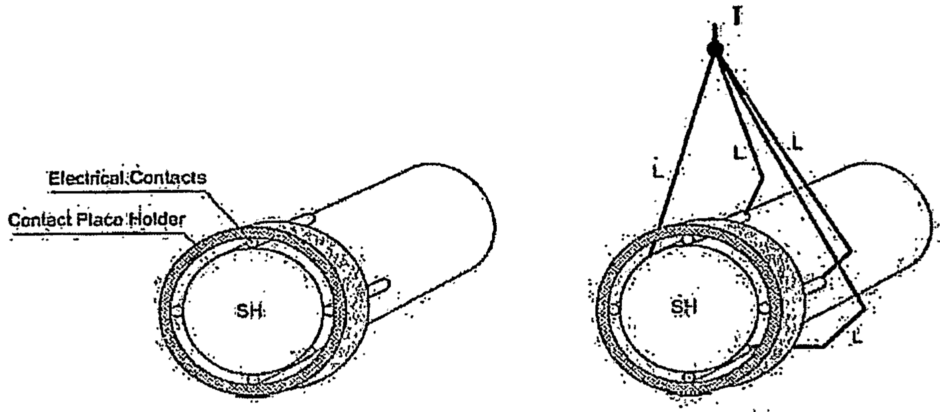


Fig 36

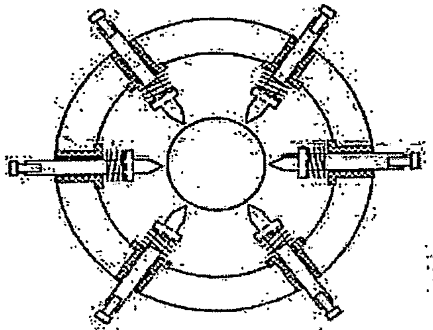


Fig 37

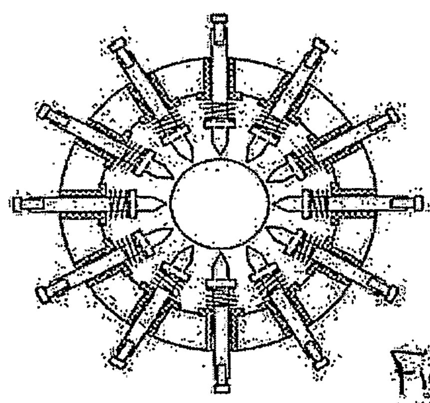


Fig 38

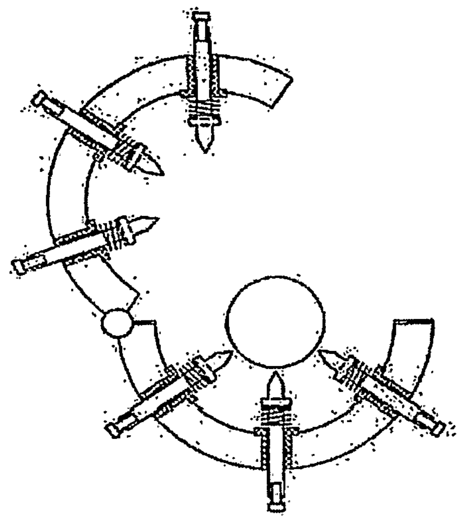


Fig 39

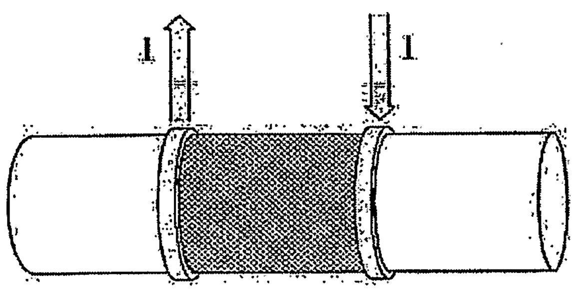


Fig 40

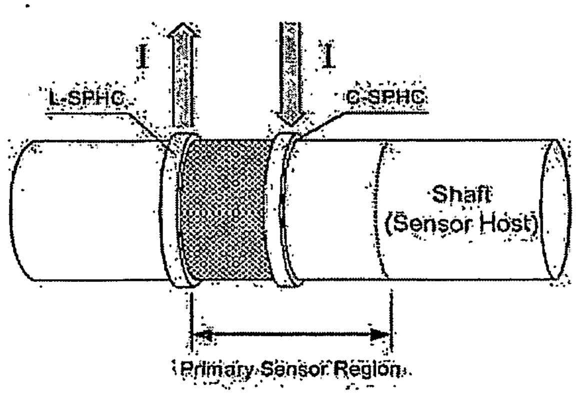


Fig 41

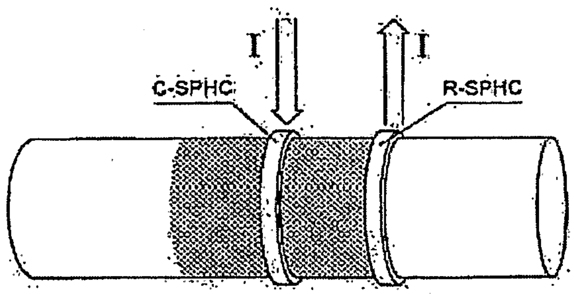


Fig 42

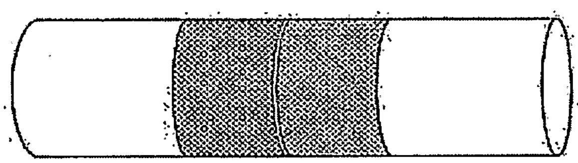


Fig 43

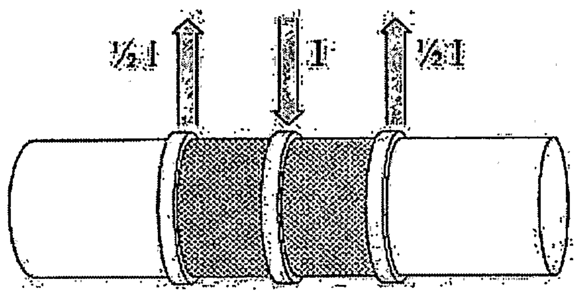


Fig 44

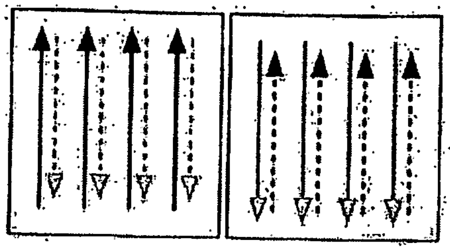


Fig. 45

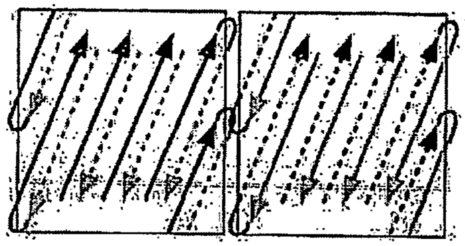


Fig. 46

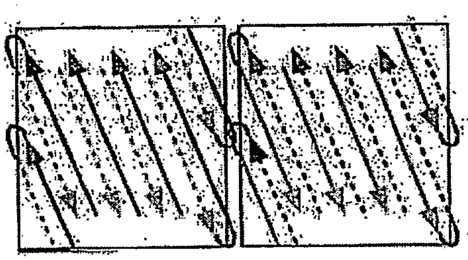
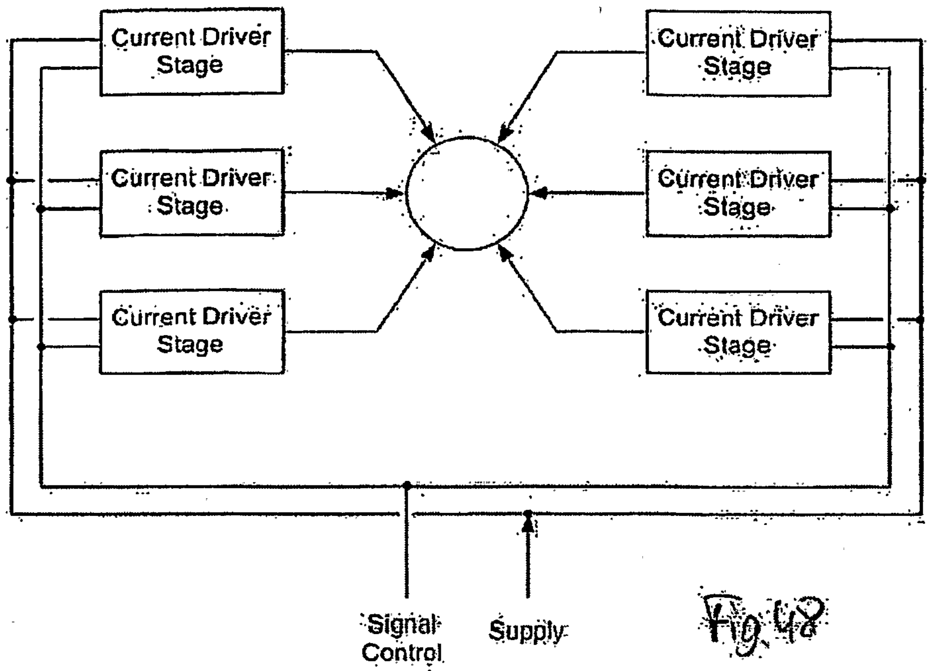
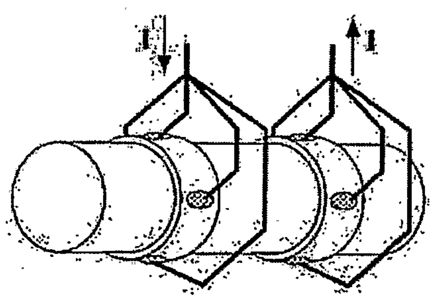


Fig. 47


Current Driver Stage
Current Driver Stage
Current Driver Stage
Current Driver Stage
Current Driver Stage
Current Driver Stage
Signal Control
Supply
Fig 48


I
I
Fig 49

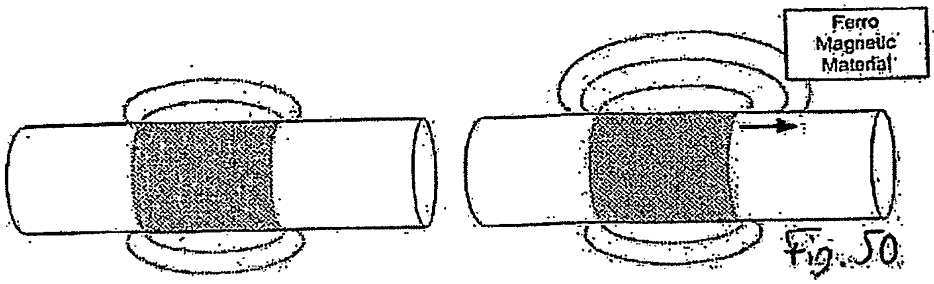


Fig. 50

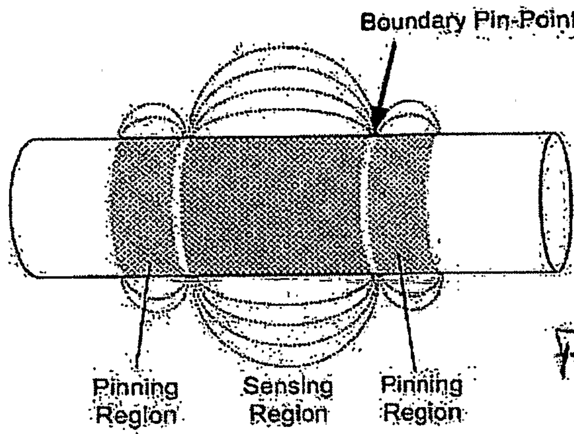


Fig. 51

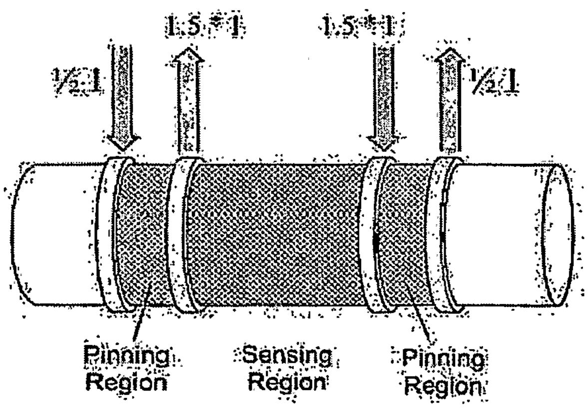


Fig. 52

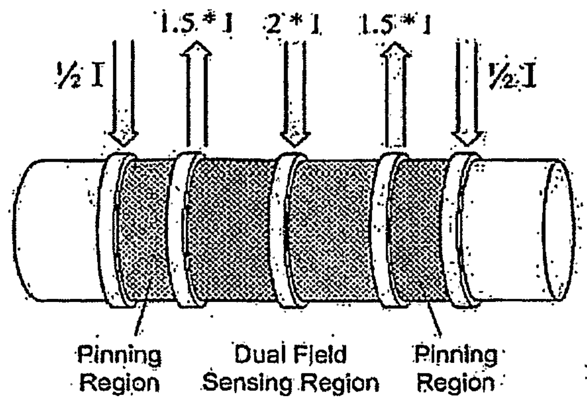


Fig. 53

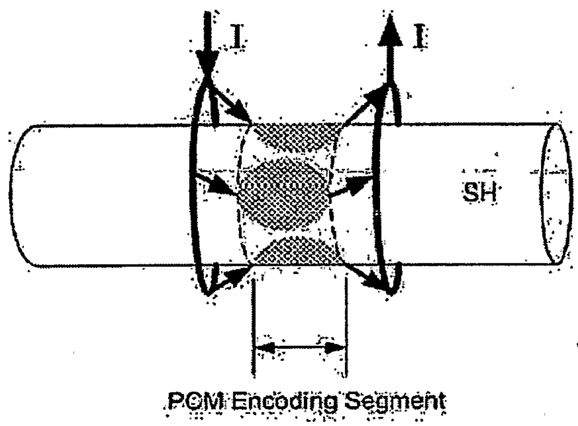


Fig. 54

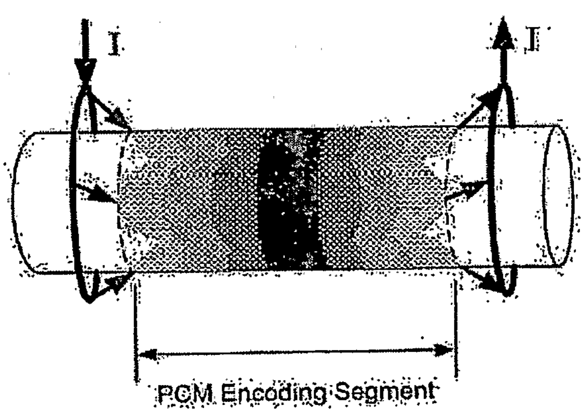
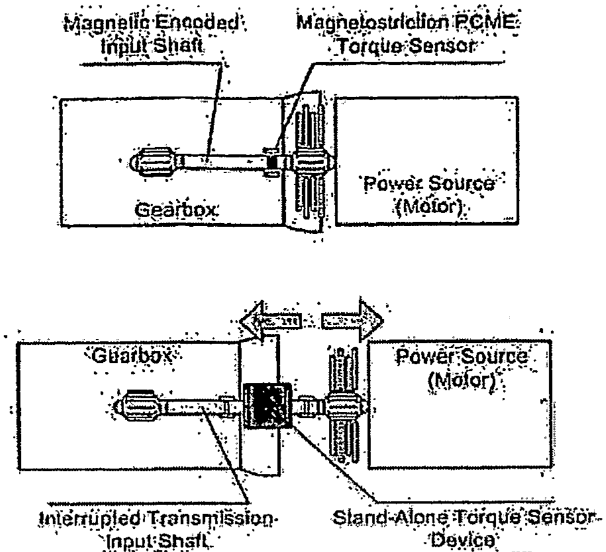
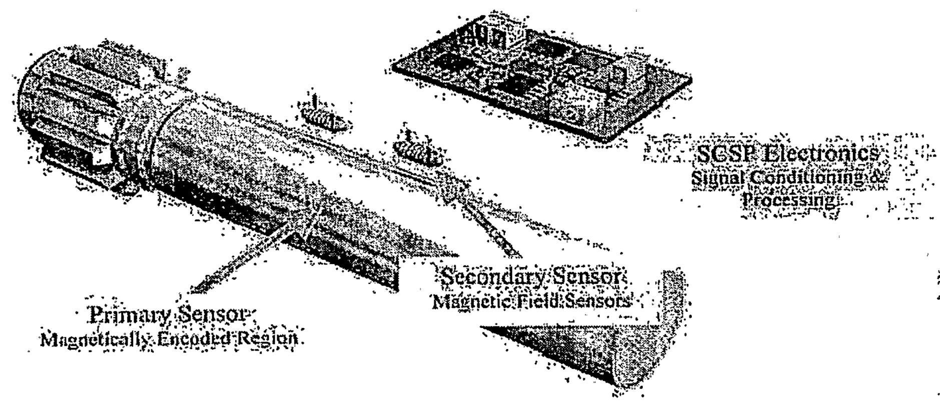


Fig. 55



Magnetic Encoded Input Shaft
Magnetostriction PCME Torque Sensor
Gearbox
Power Source (Motor)
Guarbox
Power Source (Motor)
Interrupted Transmission Input Shaft
Stand-Alone Torque Sensor Device

Fig 56



SCSP Electronics
Signal Conditioning & Processing
Secondary Sensor
Magnetic Field Sensors
Primary Sensor
Magnetically Encoded Region

Fig 57

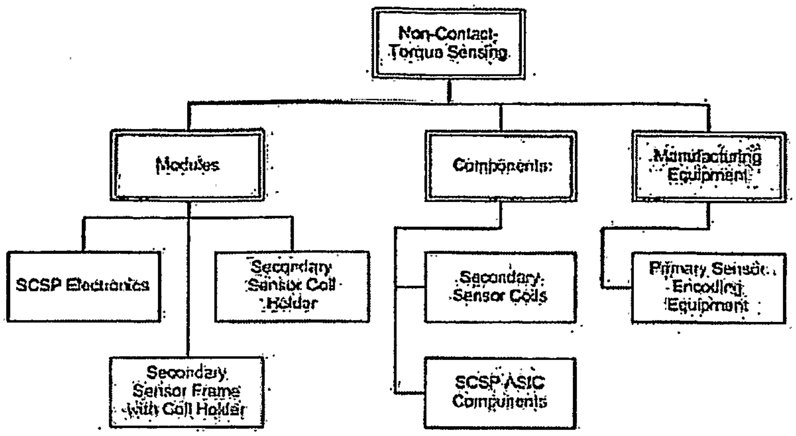


Fig. 58

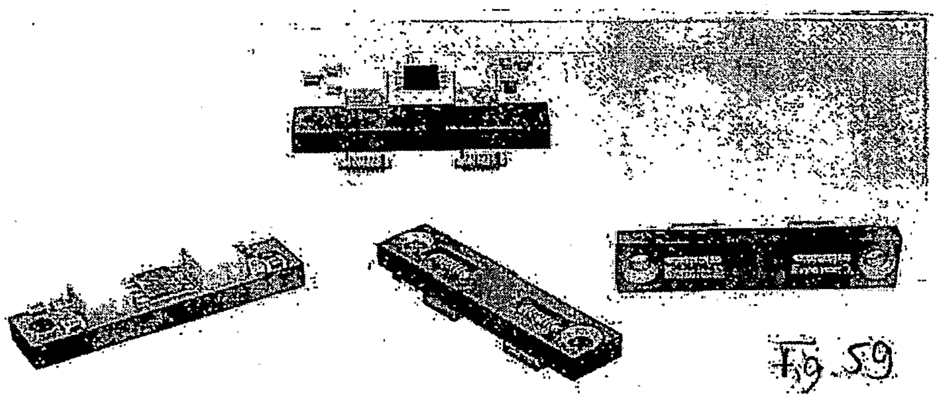


Fig. 59

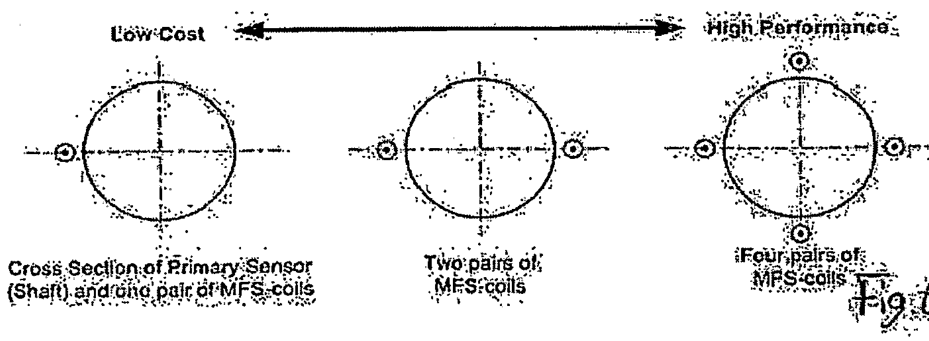
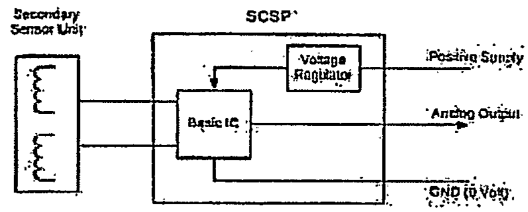
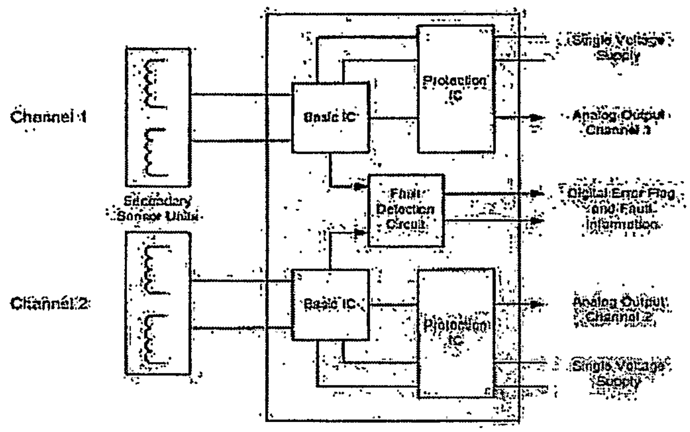


Fig 60



Secondary Sensor Unit
SCSP
Voltage Regulator
Basic IC
Positive Supply
Analog Output
GND (0 Volt)

Fig. 61



Channel 1
Channel 2
Secondary Sensor Units
Basic IC
Protection IC
Fault Detection Circuit
Basic IC
Protection IC
Single Voltage Supply
Analog Output Channel 1
Digital Error Flag and Fault Information
Analog Output Channel 2
Single Voltage Supply

Fig. 62

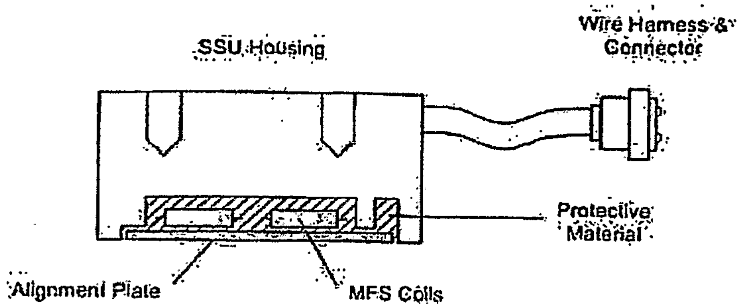

SSU Housing
Wire Harness &
Connector
Protective
Material
Alignment Plate
MFS Coils

Fig. 63

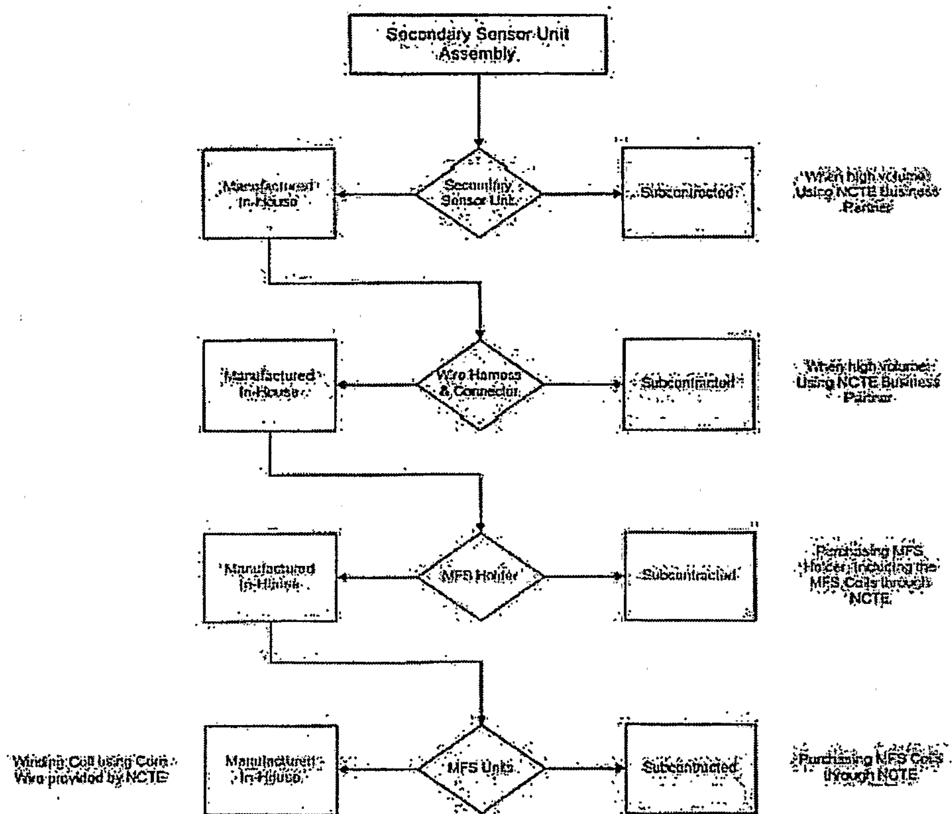
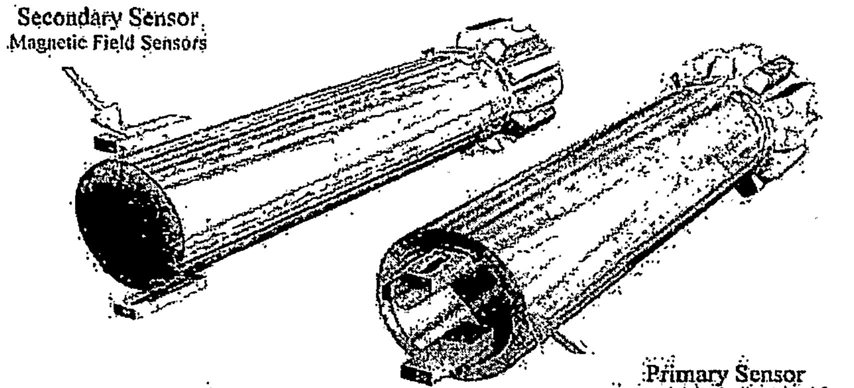
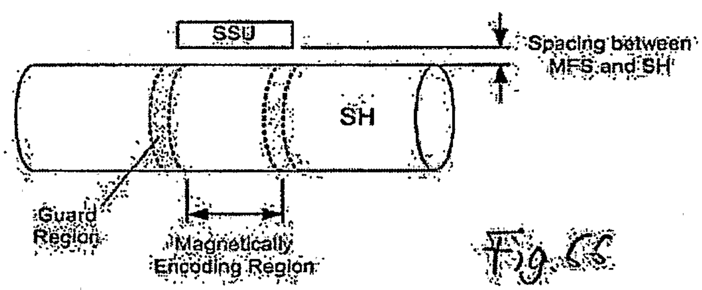

Secondary Sensor Unit
Assembly
Manufactured
In-House
Subcontracted
Wire Harness
& Connector
MFS Holder
MFS Units
Winding Coil using Core
Wire provided by NCTE

Fig. 64



Secondary Sensor
Magnetic Field Sensors
Primary Sensor
Magnetically Encoded Region

Fig. 65



SSU
Spacing between
MFS and SH
SH
Guard
Region
Magnetically
Encoding Region

Fig. 66

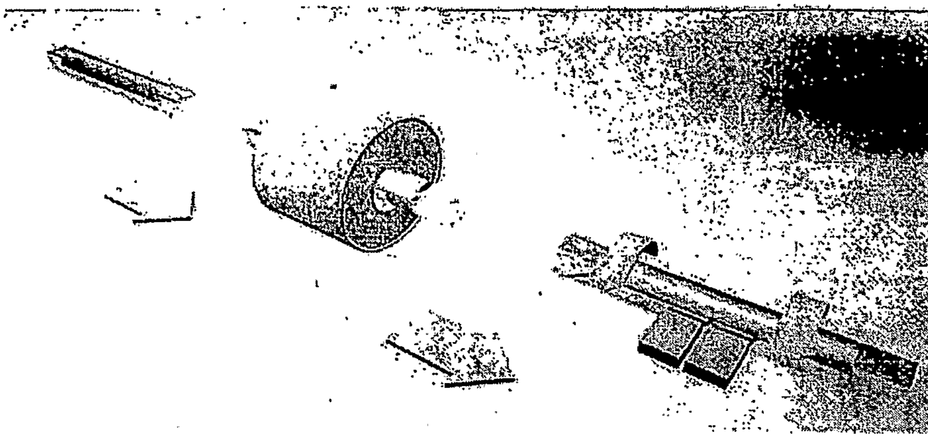


Fig. 67

PCT/EP2004/014797

25.02.05

PA 1280992

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UNITED STATES DEPARTMENT OF COMMERCE

United States Patent and Trademark Office

February 08, 2005

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APPLICATION NUMBER: ***60/629,589***
FILING DATE: ***November 19, 2004***

By Authority of the
COMMISSIONER OF PATENTS AND TRADEMARKS

N. Woodson

N. WOODSON
Certifying Officer

15866 U.S.PTO

[40124/04201]

19249 U.S.PTO
60/629589
111904

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Inventor(s)	:	**Lutz MAY** **Wolfratshauser Str. 23a** **82578 Gelting- Geretsried** **Germany** **Citizenship: Germany**
Serial No.	:	**To Be Assigned**
Filing Date	:	**Herewith**
For	:	**Sensor Device and Method of Detecting a Sensor Event**

Mail Stop: New Patent Application
Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

Please associate this application (Attorney Docket No. 40124/04201) with Customer No. 30636

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Enclosed herewith please find the following:

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2. 31 sheets of drawings.
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By: ____________________
Oleg F. Kaplun (Reg. No. 45,559)

Fay Kaplun & Marcin, LLP
150 Broadway, Suite 702
New York, NY 10038
(212) 619-6000- Telephone
(212) 619-0276- facsimile

[40124/04201]

U.S. PROVISIONAL PATENT APPLICATION

For

Sensor Device and Method of Detecting a Sensor Event

Inventor(s):

Lutz MAY

Total Pages (including title page and specification): 62

Represented by:
FAY KAPLUN & MARCIN, LLP
150 Broadway, Suite 702
New York, NY 10038
(212) 619-6000 (tel)
(212) 619-0276 (fax)
info@FKMiplaw.com

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Name: Oleg F. Kaplun, (Reg. No. 45,559)

Signature

Application No.	Our Reference	Munich,
New Application NCTENGINEERING GMBH	N 7193 / KK	19. November 2004

NCTEngineering GmbH

Otto-Hahn-Straß e 24, 85521 Ottobrunn, Deutschland

A sensor device and a method of detecting a sensor event

Background of the Invention

Field of the Invention

The present invention relates to a sensor device and to a method of detecting a sensor event.

Description of the Related Art

AD

Magnetic transducer technology finds application in the measurement of torque and position. It has been especially developed for the non-contacting measurement of torque in a shaft or any other part being subject to torque or linear motion. A rotating or reciprocating element or an element which is subject to an axial load or to shear forces can be provided with a magnetized region, i.e. a magnetic encoded region, and when the shaft is rotated or reciprocated, such a magnetic encoded region generates a characteristic signal in a magnetic field detector (like a magnetic coil) enabling to determine torque, force or position of the shaft.

For such kind of sensors which are disclosed, for instance, in WO 02/063262, it is important to have an accurately defined magnetically encoded region which can be manufactured and calibrated with low cost.

During the lifetime of a sensor, a sensor signal may undergo undesired changes due to influences like little changes of the assembly of components of the sensor, or environmental influences like temperature changes or changes of sensor material.

Summary of the Invention

It is an object of the present invention to enable an accurate operation of a sensor even in case of changes of frame conditions under which the sensor is operated.

This object is achieved by providing a sensor device and a method of detecting a sensor event according to independent aspects of the invention mentioned in the following.

In the following, different aspects of the invention will be described.

Aspects 1 and 25 are independent aspects of the invention which may be realized with or without any other means. Aspects 2 to 24 relate to preferred embodiments of aspect 1.

1. aspect: A sensor device, comprising
an object having at least one magnetically encoded region thereon;
at least two magnetic field detectors adapted to detect, as detecting signals, a magnetic field generated by the at least one magnetically encoded region in case of a sensor event;
a processing unit coupled with the at least two magnetic field detectors to be provided with the detecting signals adapted to simultaneously process the detection signals to compensate artificial differences between the detection signals.

2. aspect: The sensor device according to aspect 1,
wherein the at least one magnetically encoded region is a permanent magnetic region.

3. aspect: The sensor device according to aspect 1 or 2,
wherein the at least one magnetically encoded region is a longitudinally magnetized region of the object.

4. aspect: The sensor device according to aspect 1 or 2,
wherein the at least one magnetically encoded region is a circumferentially magnetized region of the object.

5. aspect: The sensor device according to any of aspects 1, 2 or 4,
wherein the at least one magnetically encoded region is formed by a first magnetic flow region oriented in a first direction and by a second magnetic flow region oriented in a second direction, wherein the first direction is opposite to the second direction.

6. aspect: The sensor device according to aspect 5,

wherein, in a cross-sectional view of the reciprocating object, there is the first circular magnetic flow having the first direction and a first radius and the second circular magnetic flow having the second direction and a second radius, wherein the first radius is larger than the second radius.

7. aspect: The sensor device according to aspect 1 or 2,
wherein the at least one magnetically encoded region is a magnetic element attached to the surface of the object.

8. aspect: The sensor device according to any of aspects 1 to 7,
wherein at least one of the at least two magnetic field detectors comprises at least one of the group consisting of
a coil having a coil axis oriented essentially parallel to the object;
a coil having a coil axis oriented essentially perpendicular to the object;
a Hall-effect probe;
a Giant Magnetic Resonance magnetic field sensor; and
a Magnetic Resonance magnetic field sensor.

9. aspect: The sensor device according to any of aspects 1 to 8,
being adapted as one of the group consisting of a torque sensor for detecting a torque applied to the object, a position sensor for detecting a position of the object, an axial load sensor for detecting an axial load applied to the object and a shear force sensor for detecting a shear force applied to the object.

10. aspect: The sensor device according to any of aspects 1 to 9,
wherein the object is one of the group consisting of a mining shaft, a concrete processing cylinder, a push-pull rod in a gearbox, and a shaft of an engine.

11. aspect: The sensor device according to any of aspects 1 to 10,
wherein a cross-section of the object has one of the shapes of the group consisting of an essentially circular shape, an essentially rectangular shape, an essentially triangular shape, an essentially oval shape and the shape of a toothed wheel.

12. aspect: The sensor device according to any of aspects 1 to 11,
wherein the at least two magnetic field detectors are arranged symmetrically at opposite sides of the object to compensate artificial differences between the detection signals resulting from a vibration or a positional shift of the object.

13. aspect: The sensor device according to aspect 12,
wherein the at least two magnetic field detectors are arranged symmetrically at opposite sides of the object at essentially the same distance from the object.

14. aspect: The sensor device according to aspect 12 or 13,
wherein the processing unit is adapted to compensate artificial differences between the detection signals by averaging the detection signals.

15. aspect: The sensor device according to any of aspects 1 to 10,
wherein the at least two magnetic field detectors are arranged at the same side of the object to compensate artificial differences between the detection signals resulting from changed properties of the environment or of at least one component of the sensor device.

16. aspect: The sensor device according to aspect 14,
wherein the at least two magnetic field detectors are arranged at the same side of the object at different distances from the object.

17. aspect: The sensor device according to aspect 15 or 16,

wherein the processing unit is adapted to compensate artificial differences between the detection signals based on a subtraction of the detection signals from one another.

18. aspect: The sensor device according to any of aspects 15 to 17,
wherein the at least one magnetically encoded region comprises a first magnetically encoded region and a second magnetically encoded region,

wherein the first magnetically encoded region is formed by applying a first electrical signal to a first portion of the object in absence of mechanical stress applied to the object;

wherein the second magnetically encoded region is formed by applying a second electrical signal to a second portion of the object in presence of mechanical stress applied to the object.

19. aspect: The sensor device according to aspect 18,
wherein the first electrical signal and/or the second electrical signal is a pulse signal or a sequence of subsequent pulse signals.

20. aspect: The sensor device according to aspect 19,
wherein, in a time versus current diagram, the pulse signal has a fast raising edge which is essentially vertical and has a slow falling edge.

21. aspect: The sensor device according to aspect 19 or 20,
wherein the first electrical signal and/or the second electrical signal is a current or a voltage.

22. aspect: The sensor device according to any of aspects 17 to 21,
wherein the second electrical signal is applied after having applied the first electrical signal.

23. aspect: The sensor device according to any of aspects 17 to 22,

wherein the at least one magnetically encoded region is located adjacent a first magnetic field detector, and the second magnetically encoded region is located adjacent a second magnetic field detector.

24. aspect: The sensor device according to any of aspects 17 to 23,
further comprising a manipulation unit which is coupled to the processing unit to be provided with a subtraction signal representing the subtraction of the detection signals from one another, wherein the manipulation unit is adapted to eliminate artefacts by gaining the detection signals by a factor based on the subtraction signal.

25. aspect: A method of detecting a sensor event,
the method comprising the steps of
detecting, as detecting signals, a magnetic field generated by at least one magnetically encoded region of an object in case of a sensor event by at least two magnetic field detectors;
simultaneously processing the detecting signals to compensate artificial differences between the detection signals.

In the following, the above mentioned independent aspects of the invention will be described in more detail.

One idea of the invention may be seen in the aspect to enable accurate detection by providing two or more magnetic field detectors for detecting one and the same sensor event in a redundant manner. The signals of the two magnetic field detectors are then processed in a parallel manner, and the combined analysis of these measured signals serves as a basis for an elimination of artefacts with which the detection signals may contain. By considering different measurement conditions under which these signals have been captured (e.g. different distances from a magnetically encoded region, different locations of the detectors along an extension direction of the object (preferably an elongated shaft or the like), different

magnetically encoded regions in the environment, artefacts may be eliminated or reduced. For instance, the two or more signals may be averaged, or differences between such signals may be calculated. Thus, the invention provides a signal change compensation unit to remove the negative influence of unwanted signal changes to the accuracy of the sensor.

"Artificial differences" particularly may have the meaning that the differences stem from undesired artefacts which disturb the accuracy of the measurement. The invention benefits from the different extent to that the different magnetic field coils are prone to such artefacts by simultaneously analyzing the different signals to reduce the artefacts.

For instance, undesired vibrations of a reciprocating object (the position of which shall be detected magnetically) which influence a position detection signal in a negative manner can be eliminated by arranging two magnetic field sensors symmetrically at opposing sides of the shaft. A vibration increases one signal and reduces the other one, so the averaging of both signals reduces or eliminates the influence of vibration to the detected position.

Further, ageing effects (due to irreversible demagnetization or the like) or changes in the measuring environment (for instance temperature changes or slight changes of the relative orientation of different components of an array) may occur in the case of a magnetically encoded region. To avoid a decrease of the signal intensity in this case, the difference between two detected signals located at different positions with respect to the magnetic encoding region can be used to determine an amount of signal intensity reduction due to ageing effects or the like. This difference signal can be used as a control signal to control a gain factor with which detection signals an be multiplied to compensate an artificial reduction of the intensity of a signal. In other words, an automatic gain adjustment may be performed based on the difference of two detection signals detected by two different field detecting coils. An amplifier of a signal processing electronic can be controlled on the basis of a delta between two detection signals ("automatic gain controller"). Further, if desired, in case of detecting

that a remaining signal has become too small due to ageing effects, the magnetization of the magnetically encoded region can be refreshed by a so-called PCME pulse (see description below). Such a functionality can be implemented in a torque sensor, an axial load sensor, a shear force sensor or a position sensor.

Alternatively, ageing effects can be avoided by forming a hole in the object and by fasting a permanent magnet with a very stable magnetization inside said hole. Thus, an existent object (e.g. an engine shaft) can be retrofitted in a simple manner to create a sensor device with a very small liability to ageing effects.

In the following, preferred embodiments of the sensor device according to the first independent aspect of the invention will be described. However, these embodiments also apply for the method according to the other independent aspect of the invention.

The at least one magnetically encoded region of the position sensor device may be a permanent magnetic region. The term "permanent magnetic region" refers to a magnetized material which has a remaining magnetization also in the absence of an external magnetic field. Thus, "permanent magnetic materials include ferromagnetic materials, ferrimagnetic materials, or the like. The material of such a magnetic region may be a 3d-ferromagnetic material like iron, nickel or cobalt, or may be a rare earth material (4f-magnetism).

The at least one magnetically encoded region may be a longitudinally magnetized region of the (for instance rotating or reciprocating) object. Thus, the magnetizing direction of the magnetically encoded region may be oriented along the extension direction of an elongated object. A method of manufacturing such a longitudinally magnetized region is disclosed, in a different context, in WO 02/063262 A1, and uses a separate magnetizing coil.

Alternatively, the at least one magnetically encoded region may be a circumferentially magnetized region of the object. Such a circumferentially magnetized region may particularly be adapted such that the at least one magnetically encoded region is formed by a first magnetic flow region oriented in a first direction and by a second magnetic flow region oriented in a second direction, wherein the first direction is opposite to the second direction. This embodiment can be applied to torque sensors or to position sensors. However, in case of a position sensor, the orientation can be parallel or also antiparallel.

Thus, the magnetically encoded region may be realized as two hollow cylinder-like structures which are oriented concentrically, wherein the magnetizing directions of the two concentrically arranged magnetic flow regions are preferably essentially perpendicular to one another. Such a magnetic structure can be manufactured by the PCME method described below in detail, i.e. by directly applying a magnetizing electrical current to the reciprocating object made of a magnetizable material. To produce the two opposing magnetizing flow portions, current pulses can be applied to the shaft.

Referring to the described embodiment, in a cross-sectional view of the object, there may be a first (circular) magnetic flow having the first direction and a first radius and the second (circular) magnetic flow having the second direction and a second radius, wherein the first radius is larger than the second radius.

Alternatively, the at least one magnetically encoded region may be a (separate) magnetic element attached to the surface of the object. Thus, an external element can be attached to the surface of the reciprocating object in order to form a magnetically encoded region. Such a magnetic element can be attached to the reciprocating object by adhering it (e.g. using glue), or may alternatively be fixed on the reciprocating shaft using the magnetic forces of the magnetic element.

The magnetically encoded region of the object is usually made of a magnetic or a magnetizable material. However, an object made of a non-magnetic material (like plastics or the like) may be used, when a synthetic (ferro-)magnetic magnet is attached to or embedded in the object.

Any of the magnetic field detectors may comprise a coil having a coil axis oriented essentially parallel to an extension direction of the object. Further, any of the magnetic field detectors may be realized by a coil having a coil axis oriented essentially perpendicular to the object. A coil being oriented with any other angle between coil axis and extension direction of the object is possible and falls under the scope of the invention. Alternatively to a coil in which the moving magnetically encoded region may induce an induction voltage by modulating the magnetic flow through the coil, a Hall-effect probe may be used as magnetic field detector making use of the Hall effect. Alternatively, a Giant Magnetic Resonance magnetic field sensor or a Magnetic Resonance magnetic field sensor may be used as a magnetic field detector. However, any other magnetic field detector (which is already known or which will be developed in the future) may be used to detect the presence or absence of one of the magnetically encoded regions in a sufficient close vicinity to the respective magnetic field detector.

The sensor device may be adapted as one of the group consisting of a torque sensor for detecting a torque applied to the object (when the object rotates), a position sensor for detecting a position of the object (when the object reciprocates), an axial load sensor for detecting an axial load applied to the object and a shear force sensor for detecting a shear force applied to the object.

The object may be one of the group consisting of a mining shaft, a concrete processing cylinder, a push-pull rod in a gearbox, and a shaft of an engine. The method and apparatuses of the invention may be implemented in the frame of a mining shaft, a concrete processing

cylinder, a push-pull rod in a gearbox, or a shaft of an engine. In all of these applications, the compensation of sensor signal artefacts of such a torque, force and position sensor is highly advantageous, since it allows to manufacture a highly accurate and reliably force, position and torque sensor with low costs which does not have to calibrated any time a change occurs. Particularly, mining and drilling equipment may be provided with the systems of the invention, and may be used for monitoring a drilling direction and drilling forces. Further applications of the invention are the recognition and the analysis of engine knocking.

A cross-section of the object may have one of the shapes of the group consisting of an essentially circular shape, an essentially rectangular shape and an essentially triangular shape, an essentially oval shape and the shape of a toothed wheel.

According to one embodiment, the at least two magnetic field detectors may be arranged symmetrically at opposite sides of the object to compensate artificial differences between the detection signals resulting from a vibration or a positional shift of the object. For instance, a reciprocating shaft as the object of a position sensor may reciprocate along a first direction and may be subject to undesired vibrations or (static) positional shifts along a second direction which may be oriented perpendicular to the first direction. By placing two magnetic field detectors at two opposing sides of the reciprocating object (the connection line for instance being aligned along the second direction) allows a compensation of signal disturbing vibration influence by averaging the two detection signals detected by the two magnetic field detectors.

Referring to this embodiment, the at least two magnetic field detectors are arranged symmetrically at opposite sides of the object at essentially the same distance from the object. This increases the amount of vibration influence being eliminated by the compensation calculation scheme.

Still referring to the described embodiment, the processing unit may be adapted to compensate artificial differences between the detection signals by averaging the detection signals, i.e. by calculating the mean value of the two signals.

According to an alternative embodiment, the at least two magnetic field detectors may be arranged at the same side of the object to compensate artificial differences between the detection signals resulting from changed properties of the environment or of at least one component of the sensor device. A changed property of the environment may be a changed temperature having an influence to the degree of magnetization of the magnetically encoded region. A changed property of at least one component of the sensor device may be a slightly changed geometrical arrangement of the magnetic field detectors with respect to the magnetically encoded region or a decrease of the magnetization amplitude of the magnetically encoded region due to a usage of the sensor for a very long time under harsh conditions.

Referring to this embodiment, the at least two magnetic field detectors may be arranged at the same side of the object at different distances from the object. The different distances yield different sensitivities of the at least two magnetic field detectors, so that resulting differences in the detection signals may be taken into account as useful information to compensate for artefacts to be eliminated.

Still referring to the described embodiment, the processing unit may be adapted to compensate artificial differences between the detection signals based on a subtraction of the detection signals from one another.

Particularly, the at least one magnetically encoded region may comprise a first magnetically encoded region and a second magnetically encoded region. The first magnetically encoded region may be formed by applying a first electrical signal to a first portion of the object in absence of mechanical stress (like torque) applied to the object. The second magnetically

encoded region may be formed by applying a second electrical signal to a second portion of the object in presence of mechanical stress (like a pre-selected amount of torque) applied to the object. By this concept, which is explained in further detail below (see Fig.8A to Fig.8D), an offset between signals measured in the vicinity of the first magnetically encoded region and signals measured in the vicinity of the first magnetically encoded region is generated.

The first electrical signal and/or the second electrical signal may be a pulse signal or a sequence of subsequent pulse signals. Such a pulse signal can particularly be a signal which is different from zero only for a defined interval of time.

Preferably, in a time versus current diagram, the pulse signal has a fast raising edge which is essentially vertical and has a slow falling edge. With such a pulse signal, the magnetically encoded region obtained has a high quality. It is also possible that a plurality of such pulses are subsequently applied to form a magnetically encoded region.

The first electrical signal and/or the second electrical signal may be a current or a voltage.

The second electrical signal is preferably applied after having applied the first electrical signal.

The at least one magnetically encoded region my be located adjacent a first magnetic field detector, and the second magnetically encoded region may be located adjacent a second magnetic field detector.

The sensor device of the invention may further comprise a manipulation unit which is coupled to the processing unit to be provided with a subtraction signal representing the subtraction of the detection signals from one another, wherein the manipulation unit may adapted to eliminate artefacts by gaining the detection signals by a factor based on the subtraction signal.

In other words, an output of the processing unit may be provided as a steering signal to the manipulation unit. Based on a combined analysis of the detection signals, an amount of signal change due to artefacts like age-effects may be evaluated. The manipulating unit may use this information to adjust a gain factor for sensor signals. The stronger the sensor signal is influenced by the artefact, the higher will be the gain factor, to achieve a proper compensation.

The above and other aspects, objects, features and advantages of the present invention will become apparent from the following description and the appended claim, taken in conjunction with the accompanying drawings in which like parts or elements are denoted by like reference numbers.

Brief Description of the Drawings

The accompanying drawings, which are included to provide a further understanding of the invention and constitute a part of the specification illustrate embodiments of the invention.

In the drawings:

Fig.1A shows a position sensor array according to a first embodiment of the invention.

Fig.1B shows a torque sensor array according to a second embodiment of the invention.

Fig.2A shows a shaft having a permanent magnet attached thereon, of a position or torque sensor array according to a third embodiment of the invention.

Fig.2B shows a shaft having a permanent magnet embedded therein, of a position or torque sensor array according to a forth embodiment of the invention.

Fig.2C shows a shaft having a permanent magnet embedded therein, of a position or torque sensor array, similar to the forth embodiment of the invention.

Fig.3A shows a position sensor array according to a fifth embodiment of the invention.

Fig.3B shows shafts with different cross-sectional geometry, each having a magnetically encoded region.

Fig.3C illustrates that a magnetically encoded region of a shaft may extend along a smaller or a larger portion along the shaft.

Fig.4A shows a perspective view of a position sensor array according to a sixth embodiment of the invention.

Fig.4B shows a cross-sectional view of the position sensor array according to the sixth embodiment of the invention.

Fig.5A shows perspective views of a position sensor array according to a seventh embodiment of the invention.

Fig.5B shows a cross-sectional view of the position sensor array according to the seventh embodiment of the invention.

Fig.6A shows a position sensor array according to an eighth embodiment of the invention.

Fig.6B shows a position sensor array according to a ninth embodiment of the invention.

Fig.7 shows a diagram illustrating detection signals as detected by magnetic field detection coils of position sensor array according to a ninth embodiment of the invention, and a correction.

Fig.8A to Fig.8D show different views of a torque sensor array according to a tenth embodiment of the invention.

Fig.9A and Fig.9B illustrate the gain of a detection signal in dependence of a distance of a magnetic field detector from a magnetically encoded region.

Fig.10A shows a torque sensor array according to an eleventh embodiment of the invention.

Fig.10B shows a torque sensor array according to a twelfth embodiment of the invention.

Fig.10C shown an exemplary set of parameters according to a APS system specification.

Fig.11 illustrates signal scans of a sensor device according to the invention.

Fig.12 to Fig.67 illustrate the PCME technology which, according to the invention, is preferably used to form at least one magnetically encoding region on at least part of a reciprocating shaft.

Detailed Description of Preferred Embodiments of the Invention

In the following, referring to Fig.1A, a position sensor array 100 according to a first embodiment of the invention will be described.

The position sensor device 100 comprises a reciprocating shaft 101 having a magnetically encoded region 102. Further, two magnetic field detecting coils 103, 104 are provided which are adapted to detect, as detecting signals, a magnetic field generated by the magnetically encoded region 102 in case of a reciprocation of the reciprocating shaft 101. A microprocessor 105 is coupled with the two magnetic field detecting coils 103, 104 to be provided with the detecting signals. The microprocessor 105 is adapted to simultaneously process the detection signals to compensate artificial differences between the detection signals.

The two magnetic field detecting coils 103, 104 are arranged symmetrically at opposite sides of the reciprocating shaft 101 to compensate artificial differences between the detection signals resulting from vibrations of the reciprocating shaft 101. The two magnetic field detecting coils 103, 104 are arranged symmetrically at opposite sides of the reciprocating shaft 101 at the same distance from the reciprocating shaft 101. The microprocessor 105 is adapted to compensate artificial differences between the detection signals by averaging the detection signals.

In the following, referring to Fig.1B, a torque sensor array 120 according to a second embodiment of the invention will be described.

In the case of the torque sensor device 120, the two magnetic field detecting coils 103, 104 are arranged at the same side of the rotating shaft 101 to compensate artificial differences between the detection signals resulting from changed properties of the environment or of at least one component of the sensor device 120. The microprocessor 105 is adapted to compensate artificial differences between the detection signals based on a subtraction of the detection signals from one another.

In the following, referring to Fig.2A, a shaft 101 having a permanent magnet 200 attached thereon, of a position or torque sensor array according to a third embodiment of the invention will be described.

Ageing effects (resulting from a loss of magnetization of a magnetically encoded region of a steel shaft which may occur during a long lifetime) can be avoided by fasting the permanent magnet 200 with a very stable magnetization as to be attached to the shaft 101 and covered with a protection element 202. Thus, the resulting sensor device has a very small liability to ageing effects.

Fig.2B and Fig.2C show, as an alternative configuration to Fig.2A, a shaft 101 having a permanent magnet 200 embedded in a hole 201 formed in the shaft 101, of a position or torque sensor array according to a forth embodiment of the invention.

Thus, a synthetic magnet 200 is used to generate a very strong magnetic field. The synthetic magnet 200 can be placed inside the beam/shaft 101 or can be mounted outside the beam/shaft 101.

In the following, referring to Fig.3A, a position sensor array 300 according to a fifth embodiment of the invention will be described.

The axial position sensor 300 comprises three modules: the magnetically encoded sensor host SH 101, the magnetic field sensor devices 103, 104, and a signal conditioning and signal processing electronics 301.

Fig.3B shows shafts 101 with different cross-sectional geometry, each having a magnetically encoded region 102.

Fig.3B shows cross-sections of the shafts 101 having an essentially circular shape, an essentially rectangular shape and an essentially triangular shape. Particularly, the PCME technology can be applied to shafts with a cross-section shape: round, square, rectangular, or any other shape. When using a round shaft, the shaft can rotate at any speed without interfering the position sensor signal quality.

Fig.3C illustrates that a magnetically encoded region 102 of a shaft 101 may extend along a smaller or a larger portion along the shaft 101. The magnetically encoded region of a shaft may also extend along the entire length of the shaft (not shown). The possible axial sensing range is a function of the shaft cross-section. For example, for a shaft cross section of 40 mm2, the full scale axial sensing length may range from 10 mm to 50 mm.

Fig.4A shows a perspective view and Fig.4B shows a cross-sectional view of a position sensor array 400 according to a sixth embodiment of the invention.

The magnetic field sensor devices 103, 104 can be placed on the side or on top of the magnetically processed shaft 101. An optimal spacing b between the two magnetic field sensor devices 103, 104 is a function of the (useful) axial sensing length and the distance c between the shaft 101 and the magnetic field sensor devices 103, 104.

Fig.5A shows perspective views of a position sensor array 500 according to a seventh embodiment of the invention. Fig.5B shows a cross-sectional view of the position sensor array 500.

The position sensor array 500 allows a real-time compensation of tolerances. In addition to the magnetic field detecting coils 103, 104, additional magnetic field detecting coils 501, 502 are provided and arranged symmetrically at two opposing sides of the shaft 101. All magnetic

field detecting coils 103, 104, 501, 502 are arranged within a casing 503, in which additionally a signal conditioning and signal processing electronics module 301 is located.

Undesired vibrations 504 of the reciprocating shaft 101 (reciprocating in a direction perpendicular to the paper plane of Fig.5B) which influence a position detection signal in a negative manner can be eliminated by arranging the magnetic field detecting coils 103, 104, 501, 502 symmetrically at opposing sides of the shaft 101. A vibration increases one signal and reduces the other one, so the averaging of both signals reduces or eliminates the influence of vibration to the detected position.

In the following, referring to Fig.6A, a position sensor array 600 according to an eighth embodiment of the invention will be described.

In the case of the position sensor array 600, the four magnetic field detecting coils 103, 104, 501, 502 are arranged at the same side of the shaft 101 to compensate artificial differences between the detection signals resulting from changed properties of the environment or of at least one component of the sensor device 600. The configuration of Fig.6A allows an automatic slope detection and slope control, wherein slope means the slope of a sensor signal (see Fig.7) which may undergo a change (particular a decrease) when properties of the environment or of the sensor device 600 change. With a dual channel APS design (coil system A&B), the system 600 can detect and respond to signal slope changes.

This allows a simplification of the sensor calibration, can compensate for assembly tolerances, and can compensate for slope changes caused by temperature, spacing, etc.

In the following, referring to Fig.6B, a position sensor array 650 according to a ninth embodiment of the invention will be described.

The position sensor array 650 is an integrated system in which the coils 103, 104, 501, 502 are integrated within a casing 503 and are connected to a signal conditioning and signal processing electronics module 301. The signal conditioning and signal processing electronics module 301 generates, as an output signal, a gain factor with which sensor signals may be multiplied to compensate signal changes due to changes in the environment and in the device 650 (e.g. temperature, assembly tolerances, material variations, system damages, etc.).

Fig.7 shows a diagram 700 illustrating, along an ordinate 702, detection signals as detected by magnetic field detection coils 103, 104, 501, 502 of the position sensor array 650, and along an abscissa 701 and axial movement of the shaft 101.

When ageing effects or the like occur, the slope of the curves in Fig.7 decrease, and so does the difference signal A-B, so that the change of the difference signal A-B can be used to manipulate a sensor signal in such a manner to compensate such changes.

In the following, referring to Fig.8A to Fig.8D, a torque sensor array 800 according to a tenth embodiment of the invention will be described.

The Non-Contact PCME sensing technology requires that, preferably, the Secondary Sensor is placed at a fixed distance in relation to the Primary Sensor. To give a further explanation, the "radial" spacing between the Secondary Sensor module and the Sensor Host surface (or shaft surface) should be kept constant.

The signal strength, emitted from the Primary Sensor, will degrade rapidly the further away the receiving Secondary Sensor module is placed. In case of an application where the entire sensor system is exposed to strong vibrations (example: Combustion engine, or impact power tools), it is possible that the PCME sensor output signal will show the effect of the system

vibration in form of a signal amplitude modulation. The same could happen in an application where changes in the ambient temperature has an effect on the mechanical position of the Secondary Sensor module in relation to the Primary Sensor location (example: different temperature expansions of materials used for the physical sensor design.

This issue can be controlled and dealt with by applying the proper care when designing the sensor system (using strong bearings, assuring that the temperature coefficient is matching for the different mechanical sensor modules / components). However, the circumstances may make it impossible to assure that the mechanical precision and stability required can be guarantied and therefore the “radial” spacing may vary during the use of the sensor system.

The described invention provides a fully automatic compensation for the otherwise unwanted effects when the “radial” spacing is changing between the Secondary Sensor module and the Primary Sensor. This aspect of the invention is called here “Automatic Slope Control”, or ASC.

This aspect of the invention is also capable to deal with the unwanted effects of sensor signal ageing in case the sensor system has been exposed to mechanical overload. To give a further explanation, in case the Sensor Host will be stressed to and beyond the point where “plastic” deformation of the Sensor Host is taking place, the PCME signal begins to weaken permanently (this phenomena is typical for many sensing technologies that rely on the principles of magnetostriction). This is here called “Sensor Ageing”.

The ASC technology is capable to compensate for the effects of sensor ageing.

To achieve the ASC effect, a magnetic reference signal may be placed inside the Sensor Host. The Sensor Host will then carry the magnetic encoding of the PCME technology and a magnetic reference encoding in parallel to each other. It is the objective that the magnetic

PCME encoding will continue to respond to the physical stresses applied to the Sensor Host, while the magnetic reference encoding will only react to the effects of sensor ageing.

This ASC reference signal is placed in the SH during the PCME encoding process. Normally the PCME process is applied to the Sensor Host (SH) while the SH (or shaft) is in relaxed state (no mechanical stresses are applied to the SH). In case of the ASC technology, two PCME encoding processes will take place in succession (not in parallel) while one PCME process takes place in "relaxed" state, the other PCME process takes place while a known mechanical force (like torque) is applied to the SH.

By applying mechanical stress (like a torque force) to the SH during the PCME encoding process, the output signal of the final sensor system will have an electrical offset that is proportional to the applied mechanical stress.

Referring to Fig.8A and Fig.8B, a Dual PCME Field encoding is required to achieve the ASC effect. While one PCME encoding process happen while NO mechanical forces are applied to the shaft 101, the other PCME encoding takes place while a known mechanical force (like torque) is applied to the 101. In principle there are no obligations in which order these process steps take place.

According to the described embodiment of the ASC technology, the magnetically encoded region of the sensor device 800 comprises a first magnetically encoded region 801 and a second magnetically encoded region 802. The first magnetically encoded region 801 is formed by applying a first electrical signal to a first portion of the shaft 101 in absence of mechanical stress applied to the shaft 101. The second magnetically encoded region 802 is formed by applying a second electrical signal to a second portion of the shaft 101 in presence of mechanical stress applied to the shaft 101.

The first electrical signal and the second electrical signal are each pulse signals. In a time versus current diagram, the pulse signal has a fast raising edge which is essentially vertical and has a slow falling edge (see Fig. 30). The second electrical signal is applied preferably after having applied the first electrical signal.

Referring to Fig.8C and Fig.8D, to recover the ASC reference signal, at least two MFS devices 103, 104 are needed that will form the Secondary Sensor Unit. It is preferred that the two MFS devices 103, 104 needed are mounted on the same frame to ensure that any change of spacing between the Secondary Sensor Unit and the Sensor Host (SH) 101 will effect both MFS devices 103, 104 in exactly the same way.

It is also preferred that a SCSP (Signal Conditioning & Signal Processing) electronics 301 for both channels (MFS1 103 and MFS2 104) are effected by the changes of supply voltages and ambient temperature changes in exactly the same quantitative way. Otherwise the ASC reference signal will not be reliable enough to achieve the desired performances.

As can be seen from Fig. 8C, when the SH (Sensor Host or shaft) 101 is in the relaxed state, the output signals from the two, independent working Secondary Sensor & SCSP (Signal Conditioning & Signal Processing) Channels (Output 1 and Output 2) reading the values: +2,500V and 2.000V. The difference between these two voltages is dependent on the applied mechanical force during the PCME SH processing, the gain setting of the SCSP electronics, and the spacing between the MFS and the SH-Shaft surface. In this example the difference is 2.500 V – 2.000 V = 0.500 V. This 0.500 V represent the ASC reference signal. Under normal condition the ASC reference signal remains constant.

As can be seen from Fig. 8D, when applying a specific torque force to the SH 101, the output voltages from both SCSP channels will change by the same amount. The change in output voltage is a proportional function of the applied mechanical force. However, the difference in

the output Voltage from Channel 1 and Channel 2 remains constant (in this example: 3.200 V – 2.700 V = 0.500 V).

The signal increase from channel 1 (as a consequence of the applied torque force) is the difference between the two measurements: 3.200 V – 2.500 V = 0.700 V. The signal slope is a function of the spacing between the Primary Sensor (surface of the SH) 101 to the Secondary Sensor (MFS device) 103, 104.

Referring to Fig.9A, as the spacing between the MFS (also called Secondary Sensor) 103, 104 is increasing (like from the values S1 to the value S2), the signal amplitude will drop.

Referring to Fig.9B, with increasing spacing between the Secondary Sensor (MFS device) 103, 104 and the Primary Sensor (SH surface) 101, the absolute signal amplitude will drop rapidly (function of the power to the spacing).

In the same way the signal amplitude will drop, so will the ASC signal. The ASC signal is the difference between the output voltages from Channel 1 and Channel 2.

Fig.10A shows a block diagram 1000 of the ASC electronics. In this simplified example, the sensor signal, generated by the Secondary Sensor device MFS 1 103, will be amplitude modulated in a Programmable Gain Stage 1001. The difference between the signals of MFS1 103 and MFS2 104 is processed in a comparator 1002. The output signal of the module "Comparator" 1002 is the "Gain Control Signal" of the Programmable Gain Stage 1001. The larger the signal difference between MFS1 103 and MFS2 104, the lower the gain setting of the Programmable Gain Stage 1001 has to be. The lower the signal difference between MFS1 103 and MFS2 104, the higher the gain setting of the Programmable Gain Stage 1001 has to be.

With the increase of the gain setting, the Signal-to-Noise ratio will become poorer. Meaning that at some point the signal generated by MFS1 103 is so small that a high gain setting will amplify mainly the noise and consequently the resulting "Corrected Output Signal" is no longer of any use.

In this description "in-line" or "axial" positioned MFS devices have been used. However, this technology will work the same when using radial or tangentially placed MFS devises. Which way the MFS device has to be placed depends on what mechanical forces need to be measured and what type of mechanical force has been applied to the SH during one of the PCME encoding process.

The ASC technology is a true Non-Contact solution to detect and to correct changes of the PCME output signal amplitude caused by mechanical failures of the sensor system.

The ASC technology detects and corrects the changes of the output signal amplitude, caused by sensor ageing or by changes in the spacing between the Primary and Secondary Sensor. The space changing may be caused through mechanical damages in the sensor assembly, the effects of temperature (differences in physical expansion of the sensor material), or through mechanical vibrations in the sensor system.

The ASC technology will eliminate the need for sensors "gain"-setting calibration as the ASC reference signal gives a true representation of the sensor systems response to applied mechanical forces.

This technical solution does not require any more spacing on the SH. Meaning that the mechanical dimensions and the physical design of the "dual field" PCME sensor remains the same. There is no need to attaché any device or any substance on the SH and therefore the outstanding performances of the PCME sensor are not affected by the ASC technology.

The required electronics of the ASC solution is of low complexity and can be realized in analog signal processing technology or by using mixed signal (analog and digital) technology. When using the mixed signal approach there will be no need for any additional electronic component to implement the ASC technology. Meaning: no cost increase.

The ASC technology can correct in real-time the output signal of a PCME sensor system. The output signal correction includes:

- Fully compensating the effects of unwanted changes in the spacing of the Secondary Sensor module during measurements
- Compensating the effects of sensor ageing, caused by applying a mechanical overload to the Primary Sensor device.
- Fully compensating the effects of gain changes in the SCSP electronics stages caused by the influence of ambient temperature changes.
- Eliminates the need for the sensors gain / slope calibration. The ASC reference signal can be used to define the actual sensor response to mechanical forces applied to the SH (or Primary Sensor).

The ASC technology may not add any costs in the actual sensor system and can be applied during the actual PCME encoding procedure.

The ASC technology is applicable to all PCME sensor designs where mechanical forces (like torque, axial forces, bending) or a position (rotational and linear) needs to be measured accurately. Particularly important is this technology for applications where there is a risk of mistreating the sensor system (detecting and compensating for the effects of applying a mechanical overload (resulting in Sensor Ageing): Motor Sport, Industrial Drilling Applications, Impact and Impulse Power Tools.

Fig.10B shows a block diagram 1050 of the ASC electronics according to another embodiment.

This sophisticated electronic includes a dual channel processing (slope control), temperature compensation, signal mapping (if needed or desired), and a protocol generator.

Fig.10C shown an exemplary set of parameters according to a APS system specification.

The next drawing shows the sensor system output signal as a function of the axial (in-line) location at the Primary Sensor region.

Fig.11A shows the Sensor system output signal when moving one MFS device along the PCME encoded sections (Primary Sensor region). This graph has been generated from a Dual Field PCME sensor with reversed polarity encoding (process described in Fig.8A, Fig.8B).

The reversed polarity encoding makes it simpler to cancel the effects of parallel / uniform magnetic stray fields, like the Earth Magnetic Field (EMF). This can be achieved by subtracting the output signals MFS1 from MFS2.

However, the ASC technology also works on a Dual Field PCME sensor with not reversed polarity encoding (see below).

Fig.11B shows the Sensor System output signal when moving one MFS device axially along the Primary Sensor region. This graph comes from a Dual Field, not reversed polarity PCME sensor with ASC technology. The step function in the signal lines is caused by the PCME encoding while the sensor has been under mechanical stress (like torque).

It has been described an ASC encoding process whereby only one PCME encoding step has been performed with physical load applied to the SH. It is possible to achieve a much larger signal step function when both PCME encoding steps are performed while a mechanical load is applied to the SH. However the mechanical load applied to the SH has to be in opposite direction to assure that the desired ASC reference signal can be generated.

In the following, the so-called PCME ("Pulse-Current-Modulated Encoding") Sensing Technology will be described in detail, which can, according to a preferred embodiment of the invention, be implemented to form a magnetically encoded region and to detect a position information of a reciprocating object. In the following, the PCME technology will partly described in the context of torque sensing. However, according to the invention, this concept is implemented in the context of the position sensing of the invention.

In this description, there are a number of acronyms used as otherwise some explanations and descriptions may be difficult to read. While the acronyms "ASIC", "IC", and "PCB" are already market standard definitions, there are many terms that are particularly related to the magnetostriction based NCT sensing technology. It should be noted that in this description, when there is a reference to NCT technology or to PCME, it is referred to exemplary embodiments of the present invention.

Table 1 shows a list of abbreviations used in the following description of the PCME technology.

Acronym	Description	Category
ASIC	Application Specific IC	Electronics
DF	Dual Field	Primary Sensor
EMF	Earth Magnetic Field	Test Criteria
FS	Full Scale	Test Criteria

Hot-Spotting	Sensitivity to nearby Ferro magnetic material	Specification
IC	Integrated Circuit	Electronics
MFS	Magnetic Field Sensor	Sensor Component
NCT	Non Contact Torque	Technology
PCB	Printed Circuit Board	Electronics
PCME	Pulse Current Modulated Encoding	Technology
POC	Proof-of-Concept	
RSU	Rotational Signal Uniformity	Specification
SCSP	Signal Conditioning & Signal Processing	Electronics
SF	Single Field	Primary Sensor
SH	Sensor Host	Primary Sensor
SPHC	Shaft Processing Holding Clamp	Processing Tool
SSU	Secondary Sensor Unit	Sensor Component

Table 1: List of abbreviations

The magnetic principle based mechanical-stress sensing technology allows to design and to produce a wide range of "physical-parameter-sensors" (like Force Sensing, Torque Sensing, and Material Diagnostic Analysis) that can be applied where Ferro-Magnetic materials are used. The most common technologies used to build "magnetic-principle-based" sensors are: Inductive differential displacement measurement (requires torsion shaft), measuring the changes of the materials permeability, and measuring the magnetostriction effects.

Over the last 20 years a number of different companies have developed their own and very specific solution in how to design and how to produce a magnetic principle based torque sensor (i.e. ABB, FAST, Frauenhofer Institute, FT, Kubota, MDI, NCTE, RM, Siemens, and

others). These technologies are at various development stages and differ in "how-it-works", the achievable performance, the systems reliability, and the manufacturing / system cost.

Some of these technologies require that mechanical changes are made to the shaft where torque should be measured (chevrons), or rely on the mechanical torsion effect (require a long shaft that twists under torque), or that something will be attached to the shaft itself (press-fitting a ring of certain properties to the shaft surface,), or coating of the shaft surface with a special substance. No-one has yet mastered a high-volume manufacturing process that can be applied to (almost) any shaft size, achieving tight performance tolerances, and is not based on already existing technology patents.

In the following, a magnetostriction principle based Non-Contact-Torque (NCT) Sensing Technology is described that offers to the user a whole host of new features and improved performances, previously not available. This technology enables the realization of a fully-integrated (small in space), real-time (high signal bandwidth) torque measurement, which is reliable and can be produced at an affordable cost, at any desired quantities. This technology is called: PCME (for Pulse-Current-Modulated Encoding) or Magnetostriction Transversal Torque Sensor.

The PCME technology can be applied to the shaft without making any mechanical changes to the shaft, or without attaching anything to the shaft. Most important, the PCME technology can be applied to any shaft diameter (most other technologies have here a limitation) and does not need to rotate / spin the shaft during the encoding process (very simple and low-cost manufacturing process) which makes this technology very applicable for high-volume application.

In the following, a Magnetic Field Structure (Sensor Principle) will be described.

The sensor life-time depends on a "closed-loop" magnetic field design. The PCME technology is based on two magnetic field structures, stored above each other, and running in opposite directions. When no torque stress or motion stress is applied to the shaft (also called Sensor Host, or SH) then the SH will act magnetically neutral (no magnetic field can be sensed at the outside of the SH).

Fig.12 shows that two magnetic fields are stored in the SH and running in endless circles. The outer field runs in one direction, while the inner field runs in the opposite direction.

Fig.13 illustrates that the PCME sensing technology uses two Counter-Circular magnetic field loops that are stored on top of each other (Picky-Back mode).

When mechanical stress (like reciprocation motion or torque) is applied at both ends of the PCME magnetized SH (Sensor Host, or Shaft) then the magnetic flux lines of both magnetic structures (or loops) will tilt in proportion to the applied torque.

As illustrated in Fig.14, when no mechanical stresses are applied to the SH the magnetic flux lines are running in its original path. When mechanical stresses are applied the magnetic flux lines tilt in proportion to the applied stress (like linear motion or torque).

Depending on the applied torque direction (clockwise or anti-clockwise, in relation to the SH) the magnetic flux lines will either tilt to the right or tilt to the left. Where the magnetic flux lines reach the boundary of the magnetically encoded region, the magnetic flux lines from the upper layer will join-up with the magnetic flux lines from the lower layer and visa-versa. This will then form a perfectly controlled toroidal shape.

The benefits of such a magnetic structure are:

- Reduced (almost eliminated) parasitic magnetic field structures when mechanical stress is applied to the SH (this will result in better RSU performances).
- Higher Sensor-Output Signal-Slope as there are two "active" layers that compliment each other when generating a mechanical stress related signal. Explanation: When using a single-layer sensor design, the "tilted" magnetic flux lines that exit at the encoding region boundary have to create a "return passage" from one boundary side to the other. This effort effects how much signal is available to be sensed and measured outside of the SH with the secondary sensor unit.
- There are almost no limitations on the SH (shaft) dimensions where the PCME technology will be applied to. The dual layered magnetic field structure can be adapted to any solid or hollow shaft dimensions.
- The physical dimensions and sensor performances are in a very wide range programmable and therefore can be tailored to the targeted application.
- This sensor design allows to measure mechanical stresses coming from all three dimensions axis, including in-line forces applied to the shaft (applicable as a load-cell). Explanation: Earlier magnetostriction sensor designs (for example from FAST Technology) have been limited to be sensitive in 2 dimensional axis only, and could not measure in-line forces.

Referring to Fig.15, when torque is applied to the SH, the magnetic flux lines from both Counter-Circular magnetic loops are connecting to each other at the sensor region boundaries.

When mechanical torque stress is applied to the SH then the magnetic field will no longer run around in circles but tilt slightly in proportion to the applied torque stress. This will cause the magnetic field lines from one layer to connect to the magnetic field lines in the other layer, and with this form a toroidal shape.

Referring to Fig.16, an exaggerated presentation is shown of how the magnetic flux line will form an angled toroidal structure when high levels of torque are applied to the SH.

In the following, features and benefits of the PCM-Encoding (PCME) Process will be described.

The magnetostriction NCT sensing technology from NCTE according to the present invention offers high performance sensing features like:

- No mechanical changes required on the Sensor Host (already existing shafts can be used as they are)
- Nothing has to be attached to the Sensor Host (therefore nothing can fall off or change over the shaft-lifetime = high MTBF)
- During measurement the SH can rotate, reciprocate or move at any desired speed (no limitations on rpm)
- Very good RSU (Rotational Signal Uniformity) performances
- Excellent measurement linearity (up to 0.01% of FS)
- High measurement repeatability
- Very high signal resolution (better than 14 bit)
- Very high signal bandwidth (better than 10 kHz)

Depending on the chosen type of magnetostriction sensing technology, and the chosen physical sensor design, the mechanical power transmitting shaft (also called "Sensor Host" or in short "SH") can be used "as is" without making any mechanical changes to it or without attaching anything to the shaft. This is then called a "true" Non-Contact-Torque measurement principle allowing the shaft to rotate freely at any desired speed in both directions.

The here described PCM-Encoding (PCME) manufacturing process according to an exemplary embodiment of the present invention provides additional features no other magnetostriction technology can offer (Uniqueness of this technology):

- More then three times signal strength in comparison to alternative magnetostriction encoding processes (like the "RS" process from FAST).
- Easy and simple shaft loading process (high manufacturing through-putt).
- No moving components during magnetic encoding process (low complexity manufacturing equipment = high MTBF, and lower cost).
- Process allows NCT sensor to be "fine-tuning" to achieve target accuracy of a fraction of one percent.
- Manufacturing process allows shaft "pre-processing" and "post-processing" in the same process cycle (high manufacturing through-putt).
- Sensing technology and manufacturing process is ratio-metric and therefore is applicable to all shaft or tube diameters.
- The PCM-Encoding process can be applied while the SH is already assembled (depending on accessibility) (maintenance friendly).
- Final sensor is insensitive to axial shaft movements (the actual allowable axial shaft movement depends on the physical "length" of the magnetically encoded region).
- Magnetically encoded SH remains neutral and has little to non magnetic field when no forces (like torque) are applied to the SH.
- Sensitive to mechanical forces in all three dimensional axis.

In the following, the Magnetic Flux Distribution in the SH will be described.

The PCME processing technology is based on using electrical currents, passing through the SH (Sensor Host or Shaft) to achieve the desired, permanent magnetic encoding of the Ferro-magnetic material. To achieve the desired sensor performance and features a very specific and

well controlled electrical current is required. Early experiments that used DC currents failed because of luck of understanding how small amounts and large amounts of DC electric current are travelling through a conductor (in this case the "conductor" is the mechanical power transmitting shaft, also called Sensor Host or in short "SH").

Referring to Fig.17, an assumed electrical current density in a conductor is illustrated.

It is widely assumed that the electric current density in a conductor is evenly distributed over the entire cross-section of the conductor when an electric current (DC) passes through the conductor.

Referring to Fig.18, a small electrical current forming magnetic field that ties current path in a conductor is shown.

It is our experience that when a small amount of electrical current (DC) is passing through the conductor that the current density is highest at the centre of the conductor. The two main reasons for this are: The electric current passing through a conductor generates a magnetic field that is tying together the current path in the centre of the conductor, and the impedance is the lowest in the centre of the conductor.

Referring to Fig.19, a typical flow of small electrical currents in a conductor is illustrated.

In reality, however, the electric current may not flow in a "straight" line from one connection pole to the other (similar to the shape of electric lightening in the sky).

At a certain level of electric current the generated magnetic field is large enough to cause a permanent magnetization of the Ferro-magnetic shaft material. As the electric current is flowing near or at the centre of the SH, the permanently stored magnetic field will reside at

the same location: near or at the centre of the SH. When now applying mechanical torque or linear force for oscillation/reciprocation to the shaft, then shaft internally stored magnetic field will respond by tilting its magnetic flux path in accordance to the applied mechanical force. As the permanently stored magnetic field lies deep below the shaft surface the measurable effects are very small, not uniform and therefore not sufficient to build a reliable NCT sensor system.

Referring to Fig.20, a uniform current density in a conductor at saturation level is shown.

Only at the saturation level is the electric current density (when applying DC) evenly distributed at the entire cross section of the conductor. The amount of electrical current to achieve this saturation level is extremely high and is mainly influenced by the cross section and conductivity (impedance) of the used conductor.

Referring to Fig.21, electric current travelling beneath or at the surface of the conductor (Skin-Effect) is shown.

It is also widely assumed that when passing through alternating current (like a radio frequency signal) through a conductor that the signal is passing through the skin layers of the conductor, called the Skin Effect. The chosen frequency of the alternating current defines the "Location / position" and "depth" of the Skin Effect. At high frequencies the electrical current will travel right at or near the surface of the conductor (A) while at lower frequencies (in the 5 to 10 Hz regions for a 20 mm diameter SH) the electrical alternating current will penetrate more the centre of the shafts cross section (E). Also, the relative current density is higher in the current occupied regions at higher AC frequencies in comparison to the relative current density near the centre of the shaft at very low AC frequencies (as there is more space available for the current to flow through).

Referring to Fig.22, the electrical current density of an electrical conductor (cross-section 90 deg to the current flow) when passing through the conductor an alternating current at different frequencies is illustrated.

The desired magnetic field design of the PCME sensor technology are two circular magnetic field structures, stored in two layers on top of each other ("Picky-Back"), and running in opposite direction to each other (Counter-Circular).

Again referring to Fig.13, a desired magnetic sensor structure is shown: two endless magnetic loops placed on top of each other, running in opposite directions to each other: Counter-Circular "Picky-Back" Field Design.

To make this magnetic field design highly sensitive to mechanical stresses that will be applied to the SH (shaft), and to generate the largest sensor signal possible, the desired magnetic field structure has to be placed nearest to the shaft surface. Placing the circular magnetic fields to close to the centre of the SH will cause damping of the user available sensor-output-signal slope (most of the sensor signal will travel through the Ferro-magnetic shaft material as it has a much higher permeability in comparison to air), and increases the non-uniformity of the sensor signal (in relation to shaft rotation and to axial movements of the shaft in relation to the secondary sensor.

Referring to Fig.23, magnetic field structures stored near the shaft surface and stored near the centre of the shaft are illustrated.

It may be difficult to achieve the desired permanent magnetic encoding of the SH when using AC (alternating current) as the polarity of the created magnetic field is constantly changing and therefore may act more as a Degaussing system.

The PCME technology requires that a strong electrical current ("uni-polar" or DC, to prevent erasing of the desired magnetic field structure) is travelling right below the shaft surface (to ensure that the sensor signal will be uniform and measurable at the outside of the shaft). In addition a Counter-Circular, "picky back" magnetic field structure needs to be formed.

It is possible to place the two Counter-Circular magnetic field structures in the shaft by storing them into the shaft one after each other. First the inner layer will be stored in the SH, and then the outer layer by using a weaker magnetic force (preventing that the inner layer will be neutralized and deleted by accident. To achieve this, the known "permanent" magnet encoding techniques can be applied as described in patents from FAST technology, or by using a combination of electrical current encoding and the "permanent" magnet encoding.

A much simpler and faster encoding process uses "only" electric current to achieve the desired Counter-Circular "Picky-Back" magnetic field structure. The most challenging part here is to generate the Counter-Circular magnetic field.

A uniform electrical current will produce a uniform magnetic field, running around the electrical conductor in a 90 deg angle, in relation to the current direction (A). When placing two conductors side-by-side (B) then the magnetic field between the two conductors seems to cancel-out the effect of each other (C). Although still present, there is no detectable (or measurable) magnetic field between the closely placed two conductors. When placing a number of electrical conductors side-by-side (D) the "measurable" magnetic field seems to go around the outside the surface of the "flat" shaped conductor.

Referring to Fig.24, the magnetic effects when looking at the cross-section of a conductor with a uniform current flowing through them are shown.

The "flat" or rectangle shaped conductor has now been bent into a "U"-shape. When passing an electrical current through the "U"-shaped conductor then the magnetic field following the outer dimensions of the "U"-shape is cancelling out the measurable effects in the inner halve of the "U".

Referring to Fig.25, the zone inside the "U"-shaped conductor seem to be magnetically "Neutral" when an electrical current is flowing through the conductor.

When no mechanical stress is applied to the cross-section of a "U"-shaped conductor it seems that there is no magnetic field present inside of the "U" (F). But when bending or twisting the "U"-shaped conductor the magnetic field will no longer follow its original path (90 deg angle to the current flow). Depending on the applied mechanical forces, the magnetic field begins to change slightly its path. At that time the magnetic-field-vector that is caused by the mechanical stress can be sensed and measured at the surface of the conductor, inside and outside of the "U"-shape. Note: This phenomena is applies only at very specific electrical current levels.

The same applies to the "O"-shaped conductor design. When passing a uniform electrical current through an "O"-shaped conductor (Tube) the measurable magnetic effects inside of the "O" (Tube) have cancelled-out each other (G).

Referring to Fig.26, the zone inside the "O"-shaped conductor seem to be magnetically "Neutral" when an electrical current is flowing through the conductor.

However, when mechanical stresses are applied to the "O"-shaped conductor (Tube) it becomes evident that there has been a magnetic field present at the inner side of the "O"-shaped conductor. The inner, counter directional magnetic field (as well as the outer magnetic

field) begins to tilt in relation to the applied torque stresses. This tilting field can be clearly sensed and measured.

In the following, an Encoding Pulse Design will be described.

To achieve the desired magnetic field structure (Counter-Circular, Picky-Back, Fields Design) inside the SH, according to an exemplary embodiment of a method of the present invention, unipolar electrical current pulses are passed through the Shaft (or SH). By using "pulses" the desired "Skin-Effect" can be achieved. By using a "unipolar" current direction (not changing the direction of the electrical current) the generated magnetic effect will not be erased accidentally.

The used current pulse shape is most critical to achieve the desired PCME sensor design. Each parameter has to be accurately and repeatable controlled: Current raising time, Constant current on-time, Maximal current amplitude, and Current falling time. In addition it is very critical that the current enters and exits very uniformly around the entire shaft surface.

In the following, a Rectangle Current Pulse Shape will be described.

Referring to Fig.27, a rectangle shaped electrical current pulse is illustrated.

A rectangle shaped current pulse has a fast raising positive edge and a fast falling current edge. When passing a rectangle shaped current pulse through the SH, the raising edge is responsible for forming the targeted magnetic structure of the PCME sensor while the flat "on" time and the falling edge of the rectangle shaped current pulse are counter productive.

Referring to Fig.28, a relationship between rectangles shaped Current Encoding Pulse-Width (Constant Current On-Time) and Sensor Output Signal Slope is shown.

In the following example a rectangle shaped current pulse has been used to generate and store the Couter-Circilar "Picky-Back" field in a 15 mm diameter, 14CrNi14 shaft. The pulsed electric current had its maximum at around 270 Ampere. The pulse "on-time" has been electronically controlled. Because of the high frequency component in the rising and falling edge of the encoding pulse, this experiment can not truly represent the effects of a true DC encoding SH. Therefore the Sensor-Output-Signal Slope-curve eventually flattens-out at above 20 mV/Nm when passing the Constant-Current On-Time of 1000 ms.

Without using a fast raising current-pulse edge (like using a controlled ramping slope) the sensor output signal slope would have been very poor (below 10 mV/Nm). Note: In this experiment (using 14CrNi14) the signal hysteresis was around 0.95% of the FS signal (FS = 75 Nm torque).

Referring to Fig.29, increasing the Sensor-Output Signal-Slope by using several rectangle shaped current pulses in succession is shown.

The Sensor-Output-Signal slope can be improved when using several rectangle shaped current-encoding-pulses in successions. In comparisons to other encoding-pulse-shapes the fast falling current-pulse signal slope of the rectangle shaped current pulse will prevent that the Sensor-Output-Signal slope may ever reach an optimal performance level. Meaning that after only a few current pulses (2 to 10) have been applied to the SH (or Shaft) the Sensor-Output Signal-Slope will no longer rise.

In the following, a Discharge Current Pulse Shape is described.

The Discharge-Current-Pulse has no Constant-Current ON-Time and has no fast falling edge. Therefore the primary and most felt effect in the magnetic encoding of the SH is the fast raising edge of this current pulse type.

As shown in Fig.30, a sharp raising current edge and a typical discharging curve provides best results when creating a PCME sensor.

Referring to Fig.31, a PCME Sensor-Output Signal-Slope optimization by identifying the right pulse current is illustrated.

At the very low end of the pulse current scale (0 to 75 A for a 15 mm diameter shaft, 14CrNi14 shaft material) the "Discharge-Current-Pulse type is not powerful enough to cross the magnetic threshold needed to create a lasting magnetic field inside the Ferro magnetic shaft. When increasing the pulse current amplitude the double circular magnetic field structure begins to form below the shaft surface. As the pulse current amplitude increases so does the achievable torque sensor-output signal-amplitude of the secondary sensor system. At around 400A to 425A the optimal PCME sensor design has been achieved (the two counter flowing magnetic regions have reached their most optimal distance to each other and the correct flux density for best sensor performances.

Referring to Fig.32, Sensor Host (SH) cross section with the optimal PCME electrical current density and location during the encoding pulse is illustrated.

When increasing further the pulse current amplitude the absolute, torque force related, sensor signal amplitude will further increase (curve 2) for some time while the overall PCME-typical sensor performances will decrease (curve 1). When passing 900A Pulse Current Amplitude (for a 15 mm diameter shaft) the absolute, torque force related, sensor signal amplitude will

begin to drop as well (curve 2) while the PCME sensor performances are now very poor (curve 1).

Referring to Fig.33, Sensor Host (SH) cross sections and the electrical pulse current density at different and increasing pulse current levels is shown.

As the electrical current occupies a larger cross section in the SH the spacing between the inner circular region and the outer (near the shaft surface) circular region becomes larger.

Referring to Fig.34, better PCME sensor performances will be achieved when the spacing between the Counter-Circular "Picky-Back" Field design is narrow (A).

The desired double, counter flow, circular magnetic field structure will be less able to create a close loop structure under torque forces which results in a decreasing secondary sensor signal amplitude.

Referring to Fig.35, flattening-out the current-discharge curve will also increase the Sensor-Output Signal-Slope.

When increasing the Current-Pulse discharge time (making the current pulse wider) (B) the Sensor-Output Signal-Slope will increase. However the required amount of current is very high to reduce the slope of the falling edge of the current pulse. It might be more practical to use a combination of a high current amplitude (with the optimal value) and the slowest possible discharge time to achieve the highest possible Sensor-Output Signal Slope.

In the following, Electrical Connection Devices in the frame of Primary Sensor Processing will be described.

The PCME technology (it has to be noted that the term 'PCME' technology is used to refer to exemplary embodiments of the present invention) relies on passing through the shaft very high amounts of pulse-modulated electrical current at the location where the Primary Sensor should be produced. When the surface of the shaft is very clean and highly conductive a multi-point Cupper or Gold connection may be sufficient to achieve the desired sensor signal uniformity. Important is that the Impedance is identical of each connection point to the shaft surface. This can be best achieved when assuring the cable length (L) is identical before it joins the main current connection point (I).

Referring to Fig.36, a simple electrical multi-point connection to the shaft surface is illustrated.

However, in most cases a reliable and repeatable multi-point electrical connection can be only achieved by ensuring that the impedance at each connection point is identical and constant. Using a spring pushed, sharpened connector will penetrate possible oxidation or isolation layers (maybe caused by finger prints) at the shaft surface.

Referring to Fig.37, a multi channel, electrical connecting fixture, with spring loaded contact points is illustrated.

When processing the shaft it is most important that the electrical current is injected and extracted from the shaft in the most uniform way possible. The above drawing shows several electrical, from each other insulated, connectors that are held by a fixture around the shaft. This device is called a Shaft-Processing-Holding-Clamp (or SPHC). The number of electrical connectors required in a SPHC depends on the shafts outer diameter. The larger the outer diameter, the more connectors are required. The spacing between the electrical conductors has to be identical from one connecting point to the next connecting point. This method is called Symmetrical-"Spot"-Contacts.

Referring to Fig.38, it is illustrated that increasing the number of electrical connection points will assist the efforts of entering and exiting the Pulse-Modulated electrical current. It will also increase the complexity of the required electronic control system.

Referring to Fig.39, an example of how to open the SPHC for easy shaft loading is shown.

In the following, an encoding scheme in the frame of Primary Sensor Processing will be described.

The encoding of the primary shaft can be done by using permanent magnets applied at a rotating shaft or using electric currents passing through the desired section of the shaft. When using permanent magnets a very complex, sequential procedure is necessary to put the two layers of closed loop magnetic fields, on top of each other, in the shaft. When using the PCME procedure the electric current has to enter the shaft and exit the shaft in the most symmetrical way possible to achieve the desired performances.

Referring to Fig.40, two SPHCs (Shaft Processing Holding Clamps) are placed at the borders of the planned sensing encoding region. Through one SPHC the pulsed electrical current (I) will enter the shaft, while at the second SPHC the pulsed electrical current (I) will exit the shaft. The region between the two SPHCs will then turn into the primary sensor.

This particular sensor process will produce a Single Field (SF) encoded region. One benefit of this design (in comparison to those that are described below) is that this design is insensitive to any axial shaft movements in relation to the location of the secondary sensor devices. The disadvantage of this design is that when using axial (or in-line) placed MFS coils the system will be sensitive to magnetic stray fields (like the earth magnetic field).

Referring to Fig.41, a Dual Field (DF) encoded region (meaning two independent functioning sensor regions with opposite polarity, side-by-side) allows cancelling the effects of uniform magnetic stray fields when using axial (or in-line) placed MFS coils. However, this primary sensor design also shortens the tolerable range of shaft movement in axial direction (in relation to the location of the MFS coils). There are two ways to produce a Dual Field (DF) encoded region with the PCME technology. The sequential process, where the magnetic encoded sections are produced one after each other, and the parallel process, where both magnetic encoded sections are produced at the same time.

The first process step of the sequential dual field design is to magnetically encode one sensor section (identically to the Single Field procedure), whereby the spacing between the two SPHC has to be halve of the desired final length of the Primary Sensor region. To simplify the explanations of this process we call the SPHC that is placed in the centre of the final Primary Sensor Region the Centre SPHC (C-SPHC), and the SPHC that is located at the left side of the Centre SPHC: L-SPHC.

Referring to Fig.42, the second process step of the sequential Dual Field encoding will use the SPHC that is located in the centre of the Primary Sensor region (called C-SPHC) and a second SPHC that is placed at the other side (the right side) of the centre SPHC, called R-SPHC. Important is that the current flow direction in the centre SPHC (C-SPHC) is identical at both process steps.

Referring to Fig.43, the performance of the final Primary Sensor Region depends on how close the two encoded regions can be placed in relation to each other. And this is dependent on the design of the used centre SPHC. The narrower the in-line space contact dimensions are of the C-SPHC, the better are the performances of the Dual Field PCME sensor.

Fig.44 shows the pulse application according to another exemplary embodiment of the present invention. As my be taken from the above drawing, the pulse is applied to three locations of the shaft. Due to the current distribution to both sides of the middle electrode where the current I is entered into the shaft, the current leaving the shaft at the lateral electrodes is only half the current entered at the middle electrode, namely ½ I. The electrodes are depicted as rings which dimensions are adapted to the dimensions of the outer surface of the shaft. However, it has to be noted that other electrodes may be used, such as the electrodes comprising a plurality of pin electrodes described later in this text.

Referring to Fig.45, magnetic flux directions of the two sensor sections of a Dual Field PCME sensor design are shown when no torque or linear motion stress is applied to the shaft. The counter flow magnetic flux loops do not interact with each other.

Referring to Fig.46, when torque forces or linear stress forces are applied in a particular direction then the magnetic flux loops begin to run with an increasing tilting angle inside the shaft. When the tilted magnetic flux reaches the PCME segment boundary then the flux line interacts with the counterflowing magnetic flux lines, as shown.

Referring to Fig.47, when the applied torque direction is changing (for example from clock-wise to counter-clock-wise) so will change the tilting angle of the counterflow magnetic flux structures inside the PCM Encoded shaft.
In the following, a Multi Channel Current Driver for Shaft Processing will be described.

In cases where an absolute identical impedance of the current path to the shaft surface can not be guaranteed, then electric current controlled driver stages can be used to overcome this problem.

Referring to Fig.48, a six-channel synchronized Pulse current driver system for small diameter Sensor Hosts (SH) is shown. As the shaft diameter increases so will the number of current driver channels.

In the following, Bras Ring Contacts and Symmetrical "Spot" Contacts will be described.

When the shaft diameter is relative small and the shaft surface is clean and free from any oxidations at the desired Sensing Region, then a simple "Bras"-ring (or Copper-ring) contact method can be chosen to process the Primary Sensor.

Referring to Fig.49, bras-rings (or Copper-rings) tightly fitted to the shaft surface may be used, with solder connections for the electrical wires. The area between the two Bras-rings (Copper-rings) is the encoded region.

However, it is very likely that the achievable RSU performances are much lower then when using the Symmetrical "Spot" Contact method.

In the following, a Hot-Spotting concept will be described.

A standard single field (SF) PCME sensor has very poor Hot-Spotting performances. The external magnetic flux profile of the SF PCME sensor segment (when torque is applied) is very sensitive to possible changes (in relation to Ferro magnetic material) in the nearby environment. As the magnetic boundaries of the SF encoded sensor segment are not well defined (not "Pinned Down") they can "extend" towards the direction where Ferro magnet material is placed near the PCME sensing region.

Referring to Fig.50, a PCME process magnetized sensing region is very sensitive to Ferro magnetic materials that may come close to the boundaries of the sensing regions.

To reduce the Hot-Spotting sensor sensitivity the PCME sensor segment boundaries have to be better defined by pinning them down (they can no longer move).

Referring to Fig.51, a PCME processed Sensing region with two "Pinning Field Regions" is shown, one on each side of the Sensing Region.

By placing Pinning Regions closely on either side the Sensing Region, the Sensing Region Boundary has been pinned down to a very specific location. When Ferro magnetic material is coming close to the Sensing Region, it may have an effect on the outer boundaries of the Pinning Regions, but it will have very limited effects on the Sensing Region Boundaries.

There are a number of different ways, according to exemplary embodiments of the present invention how the SH (Sensor Host) can be processed to get a Single Field (SF) Sensing Region and two Pinning Regions, one on each side of the Sensing Region. Either each region is processed after each other (Sequential Processing) or two or three regions are processed simultaneously (Parallel Processing). The Parallel Processing provides a more uniform sensor (reduced parasitic fields) but requires much higher levels of electrical current to get to the targeted sensor signal slope.

Referring to Fig.52, a parallel processing example for a Single Field (SF) PCME sensor with Pinning Regions on either side of the main sensing region is illustrated, in order to reduce (or even eliminate) Hot-Spotting.

A Dual Field PCME Sensor is less sensitive to the effects of Hot-Spotting as the sensor centre region is already Pinned-Down. However, the remaining Hot-Spotting sensitivity can be further reduced by placing Pinning Regions on either side of the Dual-Field Sensor Region.

Referring to Fig.53, a Dual Field (DF) PCME sensor with Pinning Regions either side is shown.

When Pinning Regions are not allowed or possible (example: limited axial spacing available) then the Sensing Region has to be magnetically shielded from the influences of external Ferro Magnetic Materials.

In the following, the Rotational Signal Uniformity (RSU) will be explained.

The RSU sensor performance are, according to current understanding, mainly depending on how circumferentially uniform the electrical current entered and exited the SH surface, and the physical space between the electrical current entry and exit points. The larger the spacing between the current entry and exit points, the better is the RSU performance.

Referring to Fig.54, when the spacings between the individual circumferential placed current entry points are relatively large in relation to the shaft diameter (and equally large are the spacings between the circumferentially placed current exit points) then this will result in very poor RSU performances. In such a case the length of the PCM Encoding Segment has to be as large as possible as otherwise the created magnetic field will be circumferentially non-uniform.

Referring to Fig.55, by widening the PCM Encoding Segment the circumferentially magnetic field distribution will become more uniform (and eventually almost perfect) at the halve distance between the current entry and current exit points. Therefore the RSU performance of the PCME sensor is best at the halve way-point between of the current-entry / current-exit points.

Next, the basic design issues of a NCT sensor system will be described.

Without going into the specific details of the PCM-Encoding technology, the end-user of this sensing technology need to now some design details that will allow him to apply and to use this sensing concept in his application. The following pages describe the basic elements of a magnetostriction based NCT sensor (like the primary sensor, secondary sensor, and the SCSP electronics), what the individual components look like, and what choices need to be made when integrating this technology into an already existing product.

In principle the PCME sensing technology can be used to produce a stand-alone sensor product. However, in already existing industrial applications there is little to none space available for a "stand-alone" product. The PCME technology can be applied in an existing product without the need of redesigning the final product.

In case a stand-alone torque sensor device or position detecting sensor device will be applied to a motor-transmission system it may require that the entire system need to undergo a major design change.

In the following, referring to Fig.56, a possible location of a PCME sensor at the shaft of an engine is illustrated.

Next, Sensor Components will be explained.

A non-contact magnetostriction sensor (NCT-Sensor), as shown in Fig.57, may consist, according to an exemplary embodiment of the present invention, of three main functional elements: The Primary Sensor, the Secondary Sensor, and the Signal Conditioning & Signal Processing (SCSP) electronics.

Depending on the application type (volume and quality demands, targeted manufacturing cost, manufacturing process flow) the customer can chose to purchase either the individual components to build the sensor system under his own management, or can subcontract the production of the individual modules.

Fig.58 shows a schematic illustration of components of a non-contact torque sensing device. However, these components can also be implemented in a non-contact position sensing device.

In cases where the annual production target is in the thousands of units it may be more efficient to integrate the "primary-sensor magnetic-encoding-process" into the customers manufacturing process. In such a case the customer needs to purchase application specific "magnetic encoding equipment".

In high volume applications, where cost and the integrity of the manufacturing process are critical, it is typical that NCTE supplies only the individual basic components and equipment necessary to build a non-contact sensor:

- ICs (surface mount packaged, Application-Specific Electronic Circuits)
- MFS-Coils (as part of the Secondary Sensor)
- Sensor Host Encoding Equipment (to apply the magnetic encoding on the shaft = Primary Sensor)

Depending on the required volume, the MFS-Coils can be supplied already assembled on a frame, and if desired, electrically attached to a wire harness with connector. Equally the SCSP (Signal Conditioning & Signal Processing) electronics can be supplied fully functional in PCB format, with or without the MFS-Coils embedded in the PCB.

Fig.59 shows components of a sensing device.

As can be seen from Fig.60, the number of required MFS-coils is dependent on the expected sensor performance and the mechanical tolerances of the physical sensor design. In a well designed sensor system with perfect Sensor Host (SH or magnetically encoded shaft) and minimal interferences from unwanted magnetic stray fields, only 2 MFS-coils are needed. However, if the SH is moving radial or axial in relation to the secondary sensor position by more than a few tenths of a millimeter, then the number of MFS-coils need to be increased to achieve the desired sensor performance.

In the following, a control and/or evaluation circuitry will be explained.

The SCSP electronics, according to an exemplary embodiment of the present invention, consist of the NCTE specific ICs, a number of external passive and active electronic circuits, the printed circuit board (PCB), and the SCSP housing or casing. Depending on the environment where the SCSP unit will be used the casing has to be sealed appropriately.

Depending on the application specific requirements NCTE (according to an exemplary embodiment of the present invention) offers a number of different application specific circuits:

- Basic Circuit
- Basic Circuit with integrated Voltage Regulator
- High Signal Bandwidth Circuit
- Optional High Voltage and Short Circuit Protection Device
- Optional Fault Detection Circuit

Fig.61 shows a single channel, low cost sensor electronics solution.

Fig.62 shows a dual channel, short circuit protected system design with integrated fault detection. This design consists of 5 ASIC devices and provides a high degree of system safety. The Fault-Detection IC identifies when there is a wire breakage anywhere in the sensor system, a fault with the MFS coils, or a fault in the electronic driver stages of the "Basic IC".

Next, the Secondary Sensor Unit will be explained.

The Secondary Sensor may, according to one embodiment shown in Fig.63, consist of the elements: One to eight MFS (Magnetic Field Sensor) Coils, the Alignment- & Connection-Plate, the wire harness with connector, and the Secondary-Sensor-Housing.

The MFS-coils may be mounted onto the Alignment-Plate. Usually the Alignment-Plate allows that the two connection wires of each MFS-Coil are soldered / connected in the appropriate way. The wire harness is connected to the alignment plate. This, completely assembled with the MFS-Coils and wire harness, is then embedded or held by the Secondary-Sensor-Housing.

The main element of the MFS-Coil is the core wire, which has to be made out of an amorphous-like material.

Depending on the environment where the Secondary-Sensor-Unit will be used, the assembled Alignment Plate has to be covered by protective material. This material can not cause mechanical stress or pressure on the MFS-coils when the ambient temperature is changing.

In applications where the operating temperature will not exceed +110 deg C the customer has the option to place the SCSP electronics (ASIC) inside the secondary sensor unit (SSU). While the ASIC devices can operated at temperatures above +125 deg C it will become

increasingly more difficult to compensate the temperature related signal-offset and signal-gain changes.

The recommended maximal cable length between the MFS-coils and the SCSP electronics is 2 meters. When using the appropriate connecting cable, distances of up to 10 meters are achievable. To avoid signal-cross-talk in multi-channel applications (two independent SSUs operating at the same Primary Sensor location = Redundant Sensor Function), specially shielded cable between the SSUs and the SCSP Electronics should be considered.

When planning to produce the Secondary-Sensor-Unit (SSU) the producer has to decide which part / parts of the SSU have to be purchased through subcontracting and which manufacturing steps will be made in-house.

In the following, Secondary Sensor Unit Manufacturing Options will be described.

When integrating the NCT-Sensor into a customized tool or standard transmission system then the systems manufacturer has several options to choose from:

- custom made SSU (including the wire harness and connector)
- selected modules or components; the final SSU assembly and system test may be done under the customer's management.
- only the essential components (MFS-coils or MFS-core-wire, Application specific ICs) and will produce the SSU in-house.

Fig.64 illustrates an exemplary embodiment of a Secondary Sensor Unit Assembly.

Next, a Primary Sensor Design is explained.

The SSU (Secondary Sensor Units) can be placed outside the magnetically encoded SH (Sensor Host) or, in case the SH is hollow, inside the SH. The achievable sensor signal amplitude is of equal strength but has a much better signal-to-noise performance when placed inside the hollow shaft.

Fig.65 illustrates two configurations of the geometrical arrangement of Primary Sensor and Secondary Sensor.

Improved sensor performances may be achieved when the magnetic encoding process is applied to a straight and parallel section of the SH (shaft). For a shaft with 15 mm to 25 mm diameter the optimal minimum length of the Magnetically Encoded Region is 25 mm. The sensor performances will further improve if the region can be made as long as 45 mm (adding Guard Regions). In complex and highly integrated transmission (gearbox) systems it will be difficult to find such space. Under more ideal circumstances, the Magnetically Encoding Region can be as short as 14 mm, but this bears the risk that not all of the desired sensor performances can be achieved.
As illustrated in Fig.66, the spacing between the SSU (Secondary Sensor Unit) and the Sensor Host surface, according to an exemplary embodiment of the present invention, should be held as small as possible to achieve the best possible signal quality.

Next, the Primary Sensor Encoding Equipment will be described.

An example is shown in Fig.67.

Depending on which magnetostriction sensing technology will be chosen, the Sensor Host (SH) needs to be processed and treated accordingly. The technologies vary by a great deal from each other (ABB, FAST, FT, Kubota, MDI, NCTE, RM, Siemens, ...) and so does the processing equipment required. Some of the available magnetostriction sensing technologies

do not need any physical changes to be made on the SH and rely only on magnetic processing (MDI, FAST, NCTE).

While the MDI technology is a two phase process, the FAST technology is a three phase process, and the NCTE technology a one phase process, called PCM Encoding.

One should be aware that after the magnetic processing, the Sensor Host (SH or Shaft), has become a "precision measurement" device and has to be treated accordingly. The magnetic processing should be the very last step before the treated SH is carefully placed in its final location.

The magnetic processing should be an integral part of the customer's production process (in-house magnetic processing) under the following circumstances:

- High production quantities (like in the thousands)
- Heavy or difficult to handle SH (e.g. high shipping costs)
- Very specific quality and inspection demands (e.g. defense applications)

In all other cases it may be more cost effective to get the SH magnetically treated by a qualified and authorized subcontractor, such as NCTE. For the "in-house" magnetic processing dedicated manufacturing equipment is required. Such equipment can be operated fully manually, semi-automated, and fully automated. Depending on the complexity and automation level the equipment can cost anywhere from EUR 20k to above EUR 500k.

It should be noted that the term "comprising" does not exclude other elements or steps and the "a" or "an" does not exclude a plurality. Also elements described in association with different embodiments may be combined.

What Is claimed is:

A sensor device, comprising
an object having at least one magnetically encoded region thereon;
at least two magnetic field detectors adapted to detect, as detecting signals, a magnetic field generated by the at least one magnetically encoded region in case of a sensor event;
a processing unit coupled with the at least two magnetic field detectors to be provided with the detecting signals adapted to simultaneously process the detection signals to compensate artificial differences between the detection signals;
wherein the at least one magnetically encoded region is a circumferentially magnetized region of the object;
wherein the at least one magnetically encoded region is formed by a first magnetic flow region oriented in a first direction and by a second magnetic flow region oriented in a second direction, wherein the first direction is opposite to the second direction;
wherein, in a cross-sectional view of the reciprocating object, there is the first circular magnetic flow having the first direction and a first radius and the second circular magnetic flow having the second direction and a second radius, wherein the first radius is larger than the second radius;
wherein each of the at least two magnetic field detectors is a coil having a coil axis oriented essentially parallel to the object;
wherein the at least two magnetic field detectors are arranged symmetrically at opposite sides of the object to compensate artificial differences between the detection signals resulting from vibrations of the object;
wherein the at least two magnetic field detectors are arranged symmetrically at opposite sides of the object at the same distance from the object;
wherein the processing unit is adapted to compensate artificial differences between the detection signals by averaging the detection signals.

Abstract

A sensor device and a method of detecting a sensor event

A sensor device comprises an object having at least one magnetically encoded region thereon, at least two magnetic field detectors adapted to detect, as detecting signals, a magnetic field generated by the at least one magnetically encoded region in case of a sensor event, and a processing unit coupled with the at least two magnetic field detectors to be provided with the detecting signals adapted to simultaneously process the detection signals to compensate artificial differences between the detection signals.

(Fig.6A)

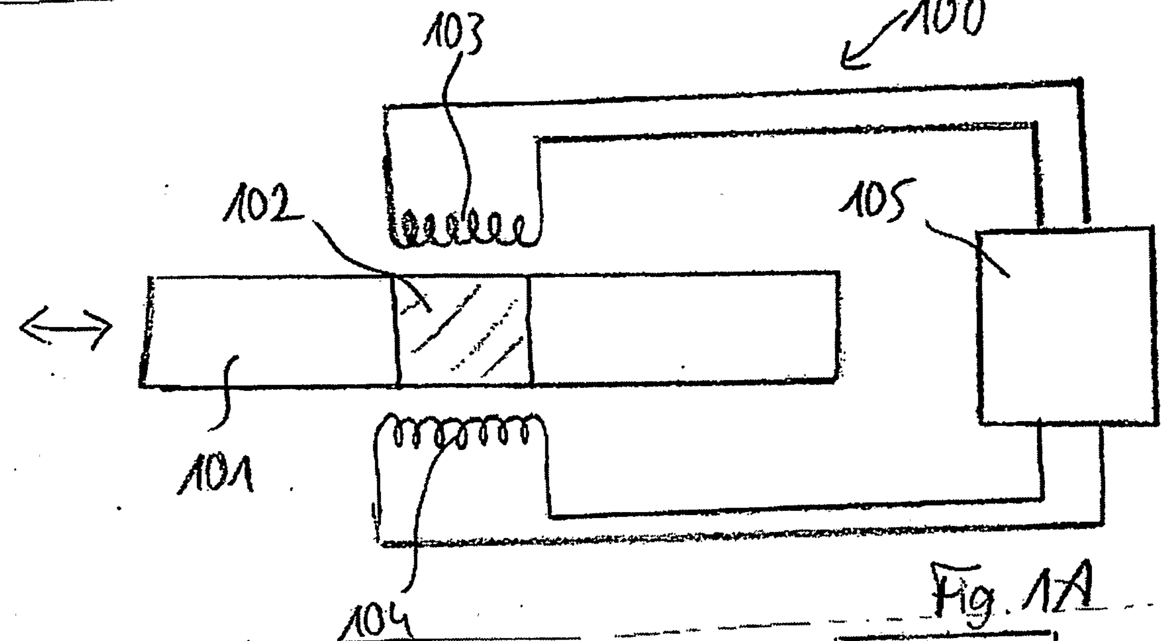


Fig. 1A

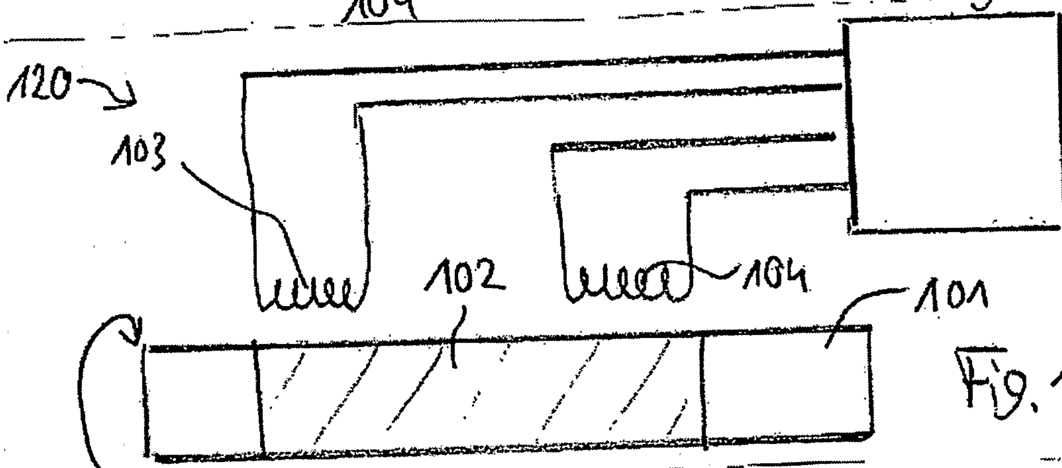


Fig. 1B

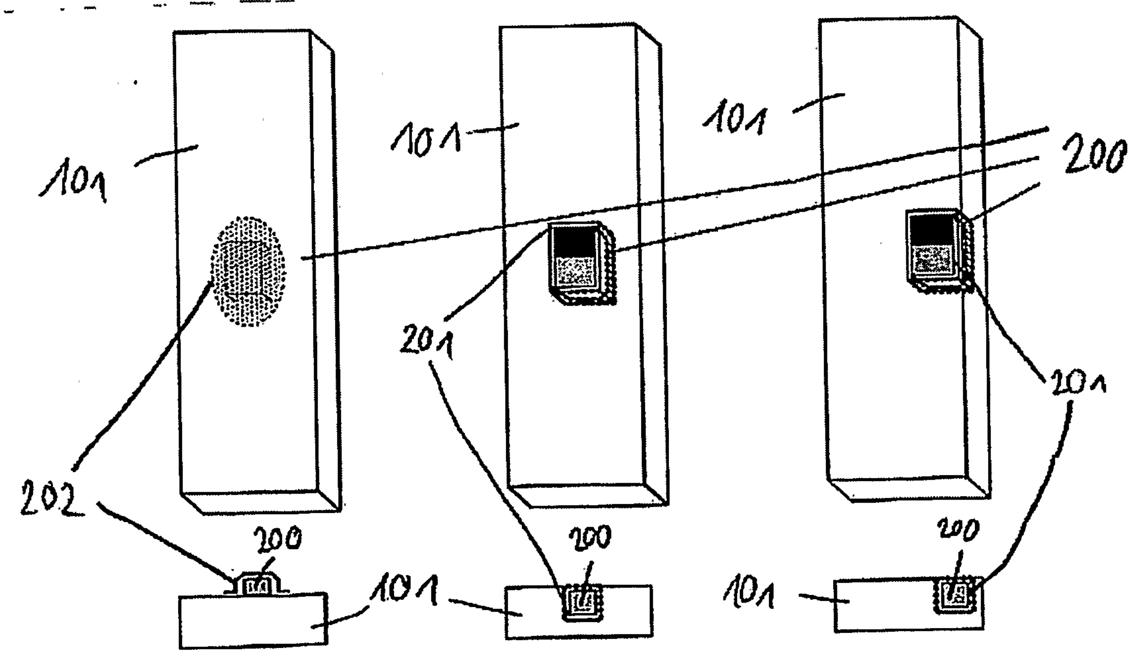
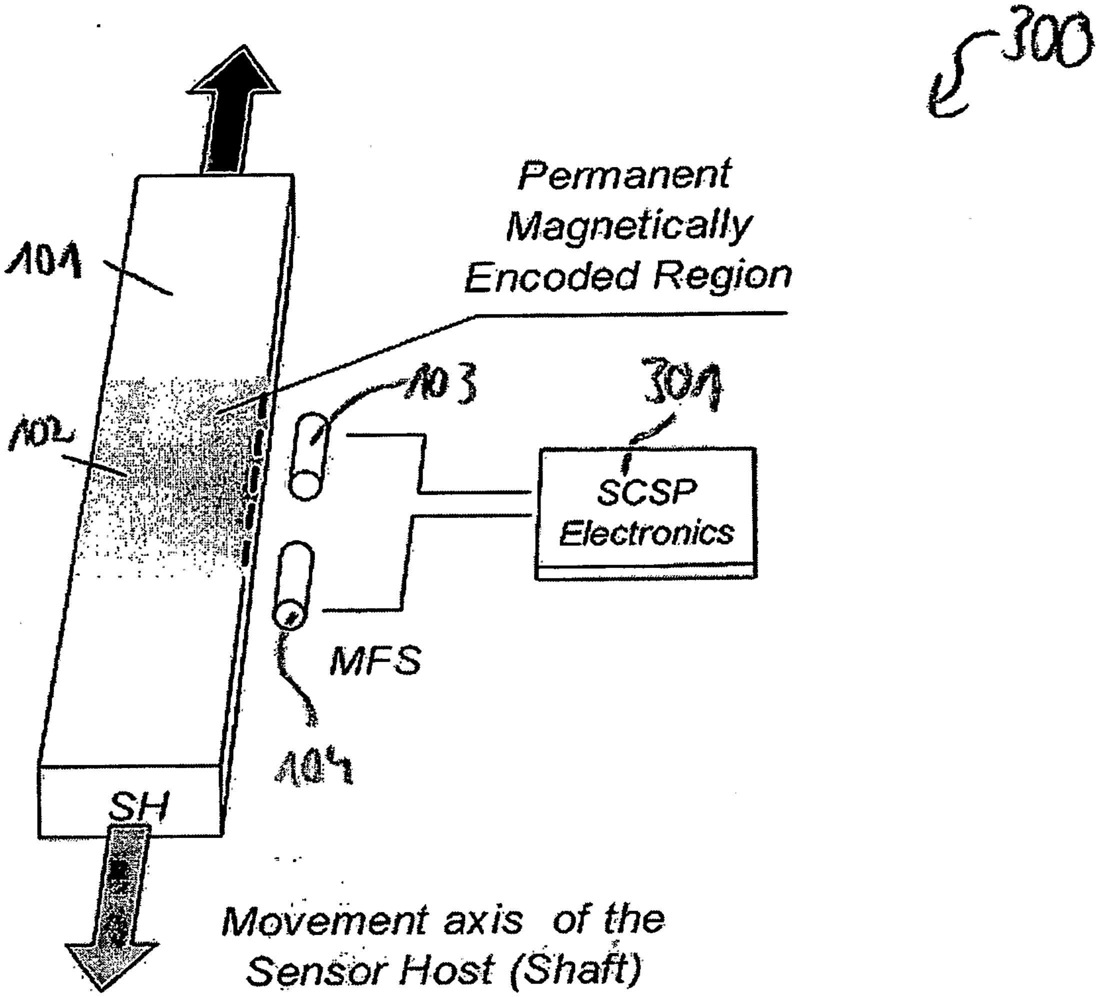
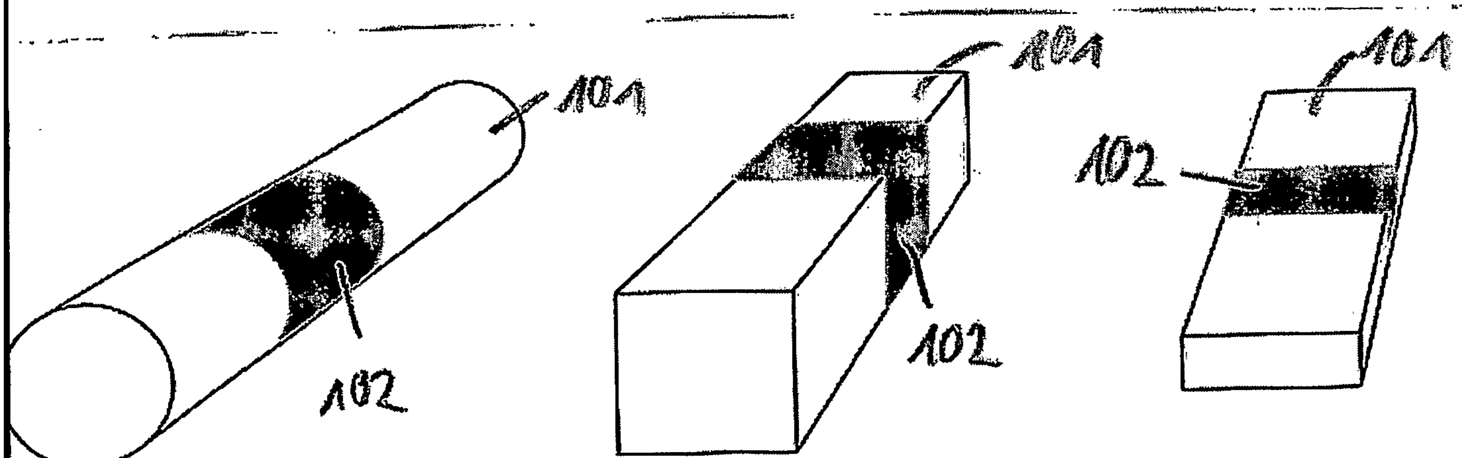


Fig. 2A Fig. 2B Fig. 2C



300
Permanent Magnetically Encoded Region
101
102
103
301
SCSP Electronics
MFS
104
SH
Movement axis of the Sensor Host (Shaft)

Fig. 3A



101
102
101
102
101
102

Fig. 3B

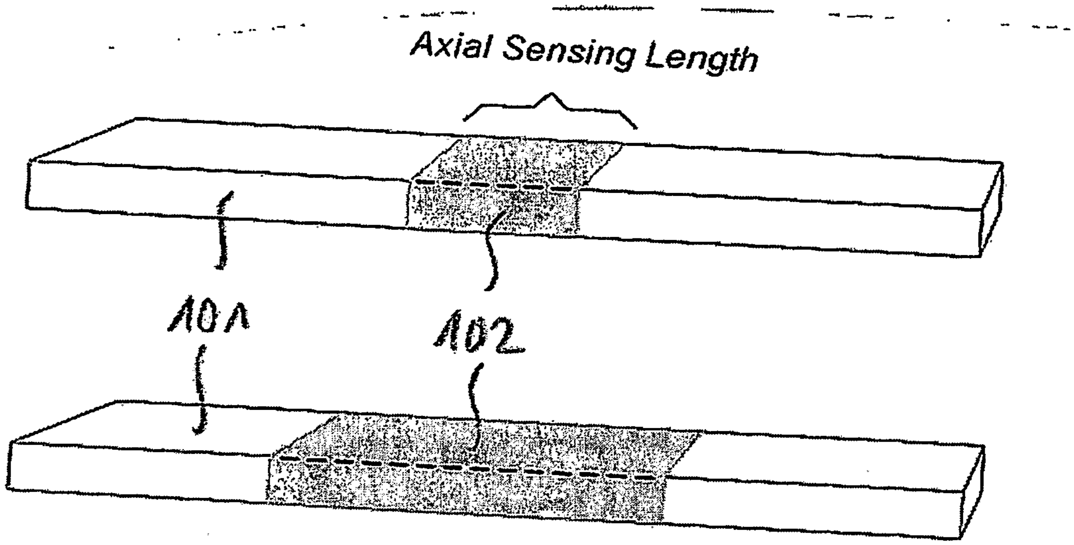


Fig.3C

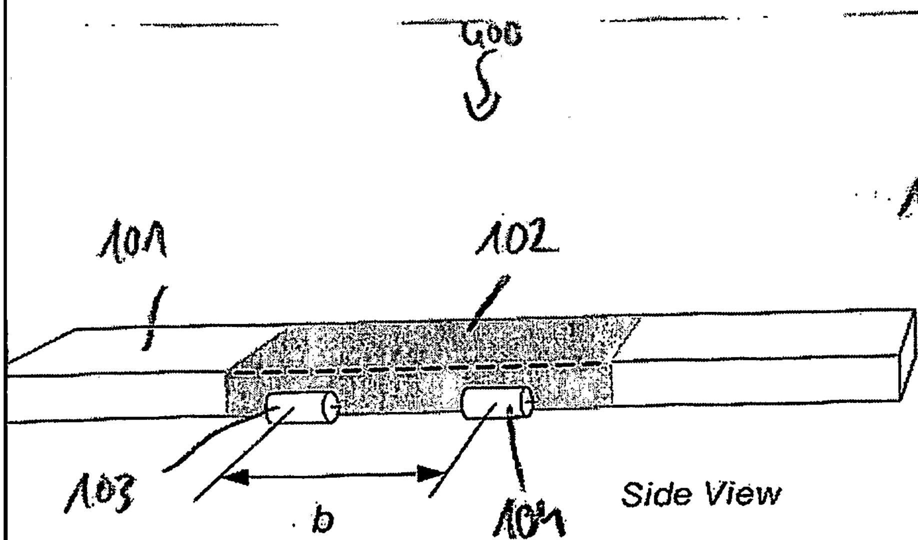


Fig.4A

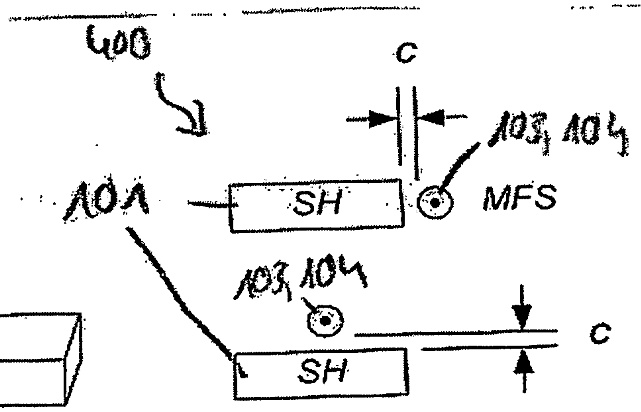


Fig.4B

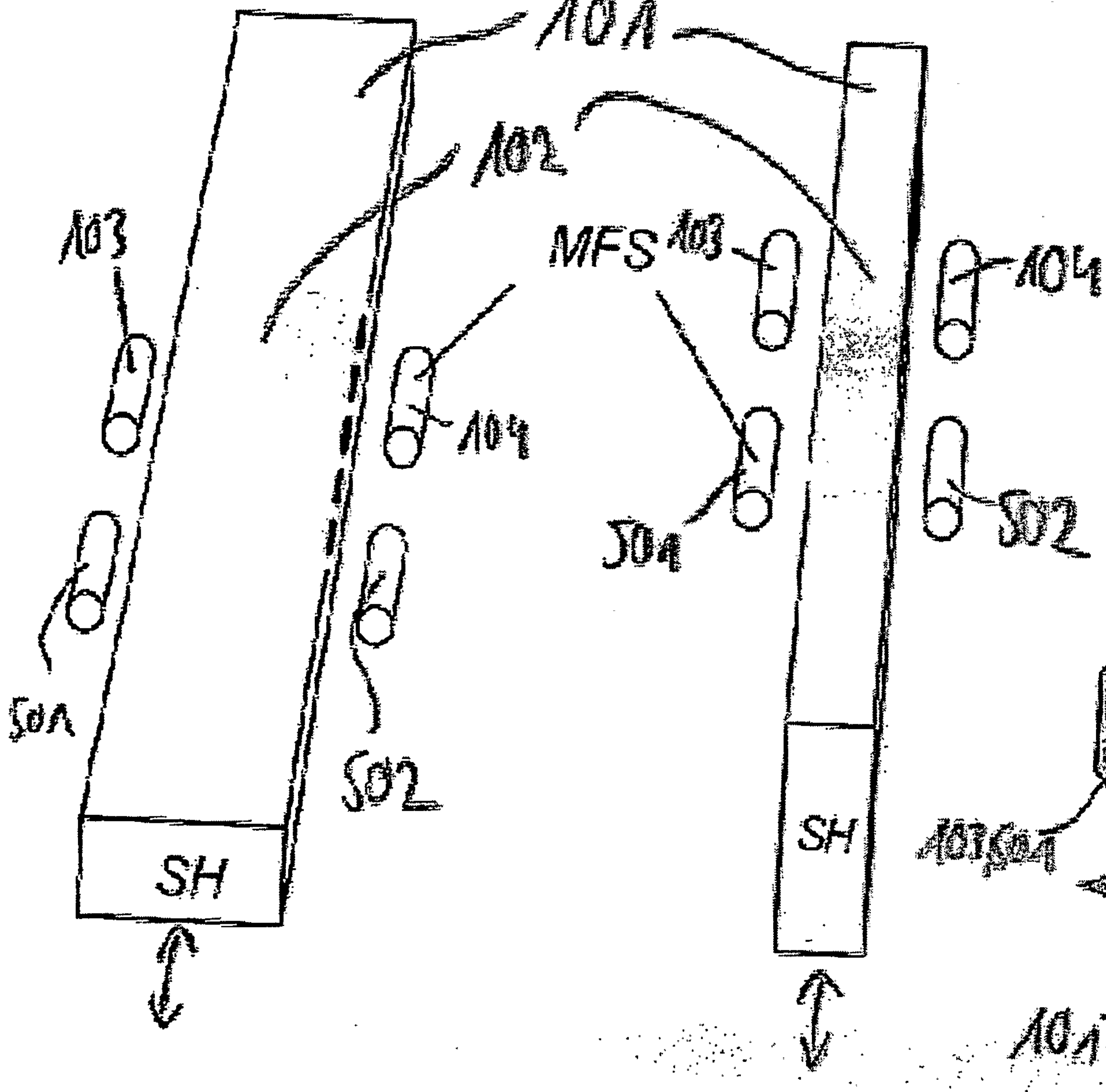

101
102
103
104
MFS
501
502
504
SH

Fig. 5A

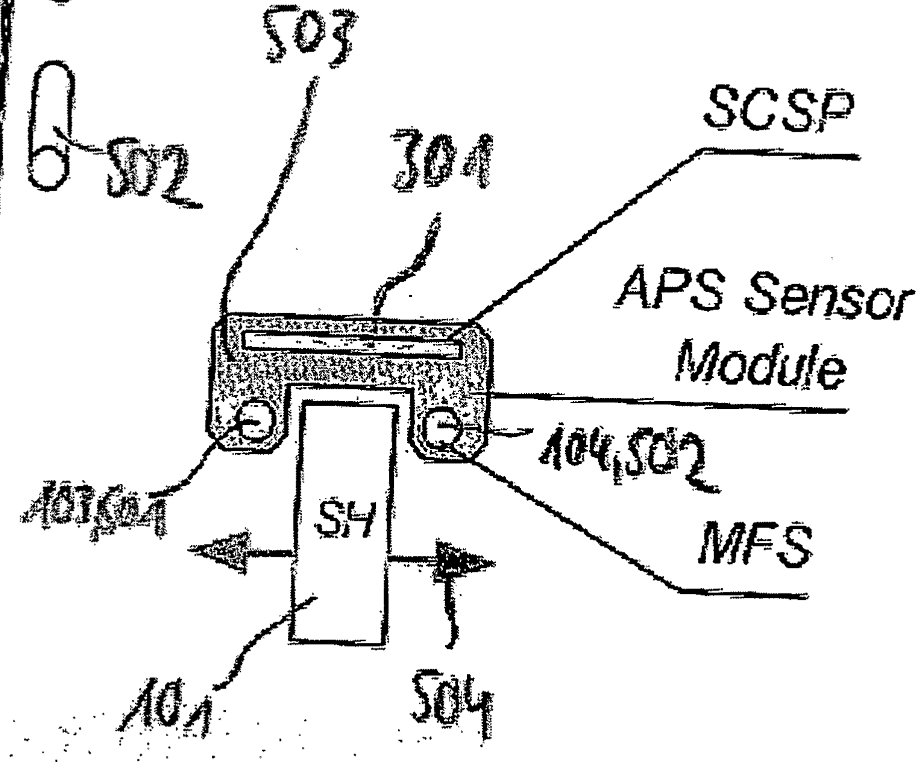

503
301
SCSP
APS Sensor
Module
104,502
MFS
103,501
SH
101
504

Fig. 5B

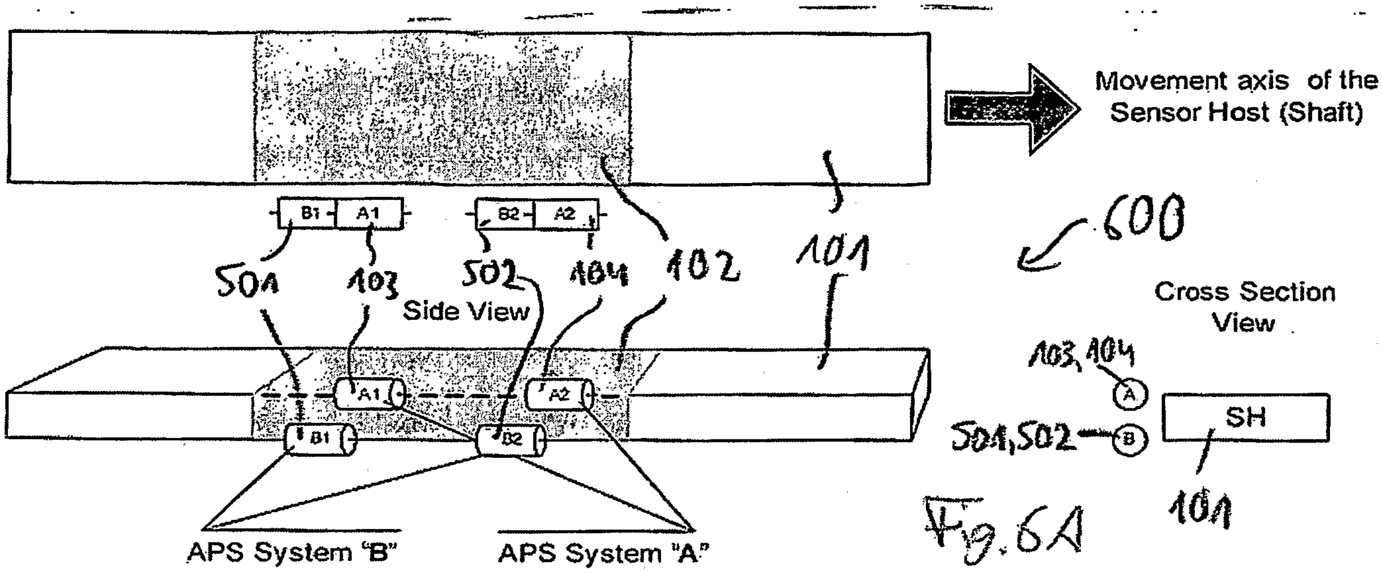


Fig. 6A

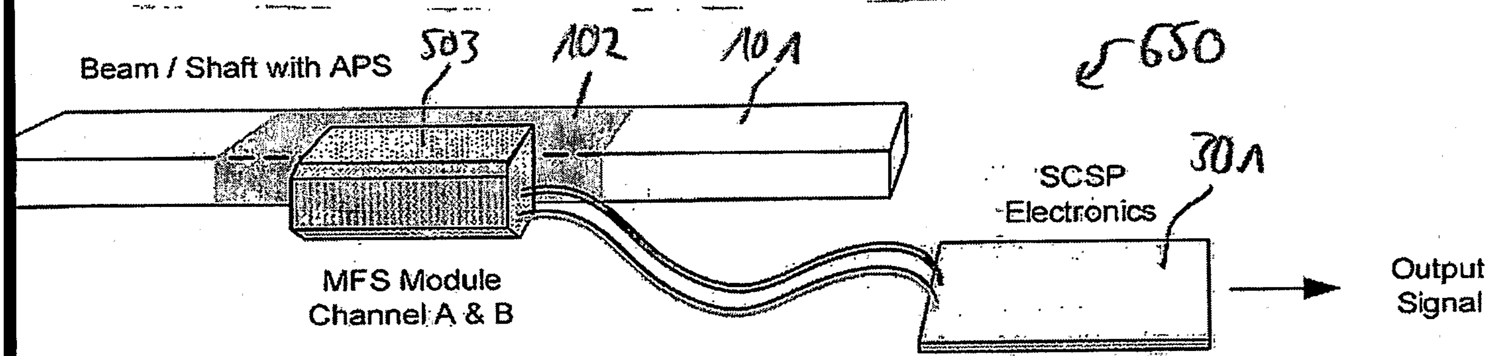


Fig. 6B

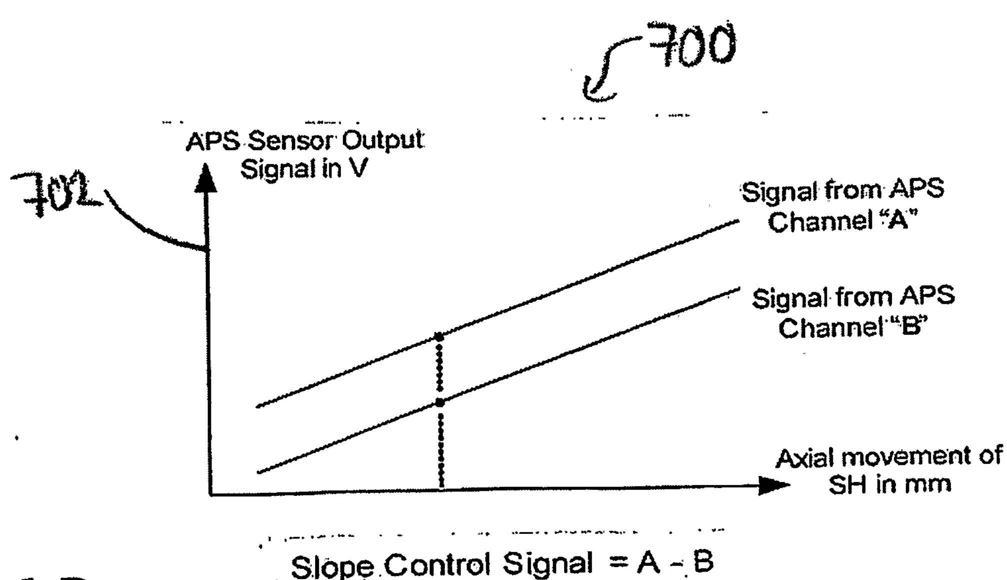
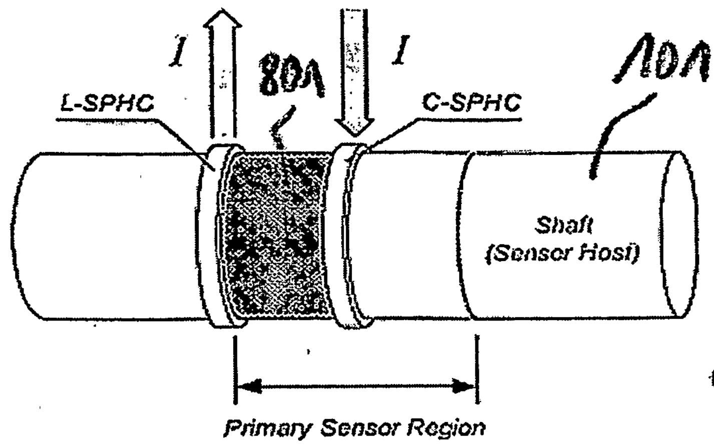


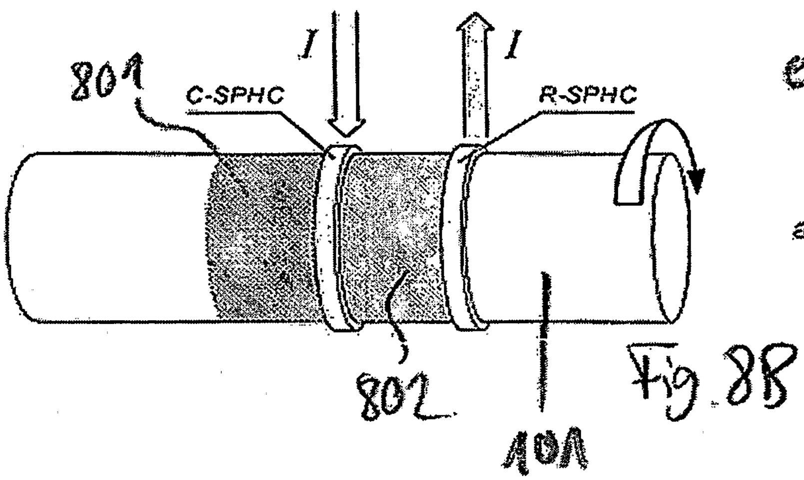
Fig. 7



Encoding Step 1: PCME process applied to SH while no mechanical forces are applied to SH

Fig. 8A

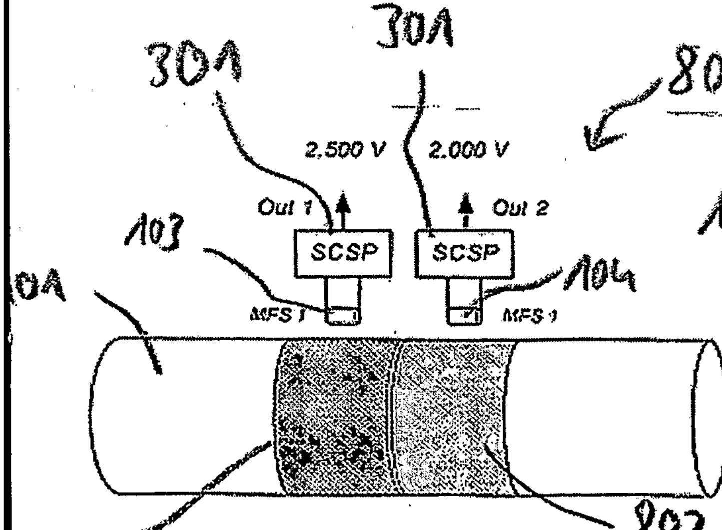
800



Encoding Step 2: PCME process applied to SH while a known mechanical forces is applied to SH

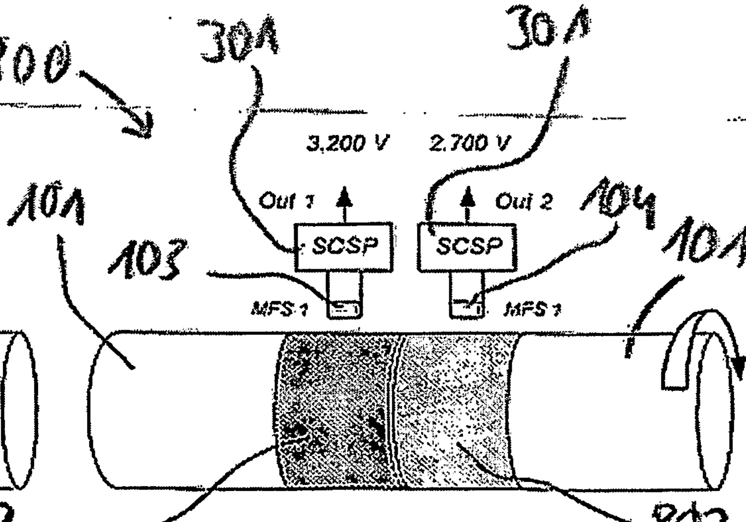
Fig. 8B

800



PCME Sensor with ASC technology when NO mechanical forces applied

Fig. 8C



PCME Sensor with ASC technology when specific torque force applied

Fig. 8D

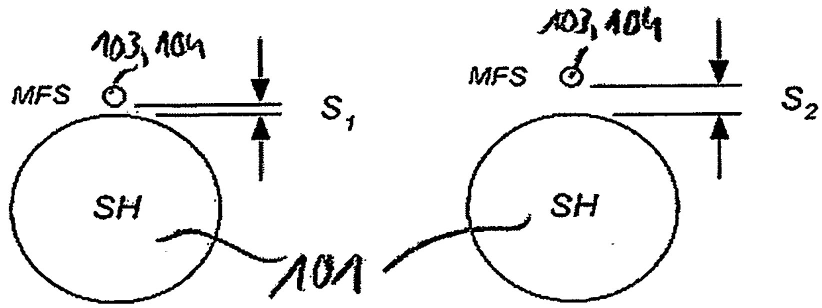


Fig. 9A

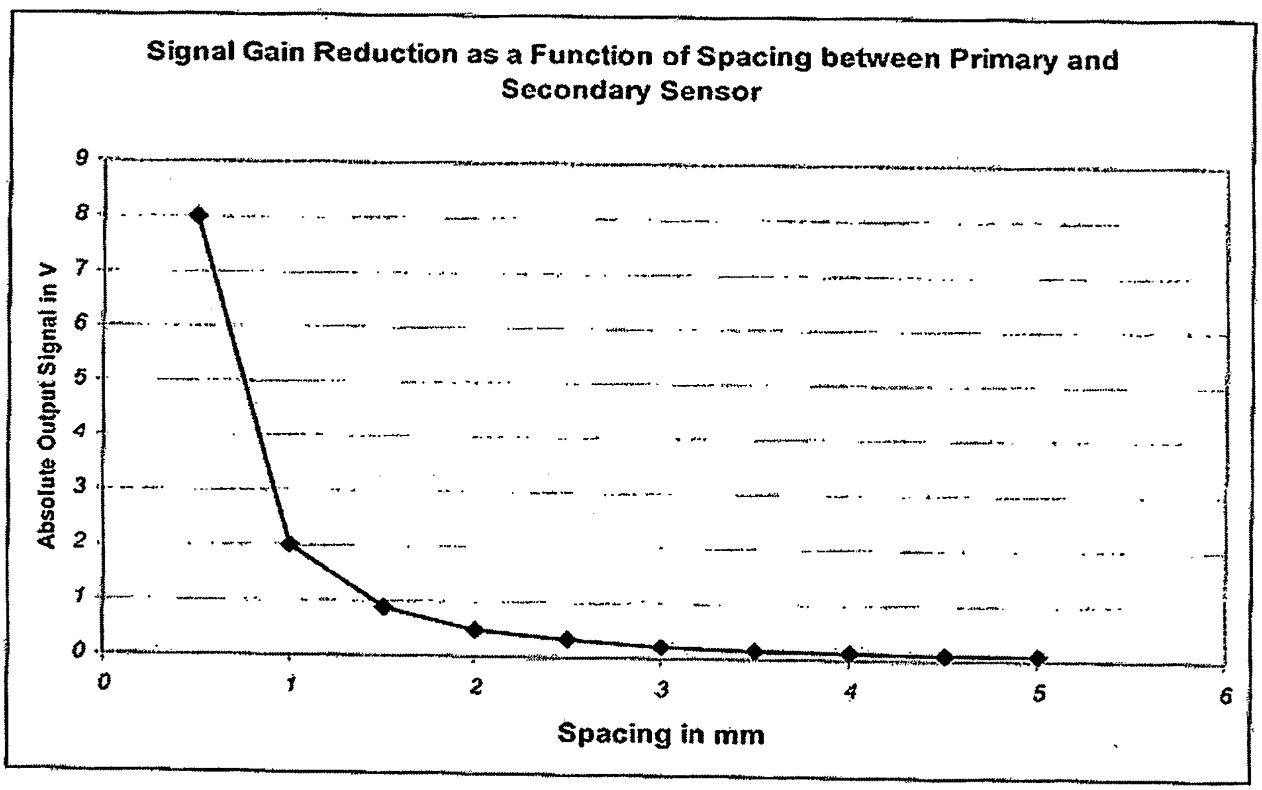


Fig. 9B

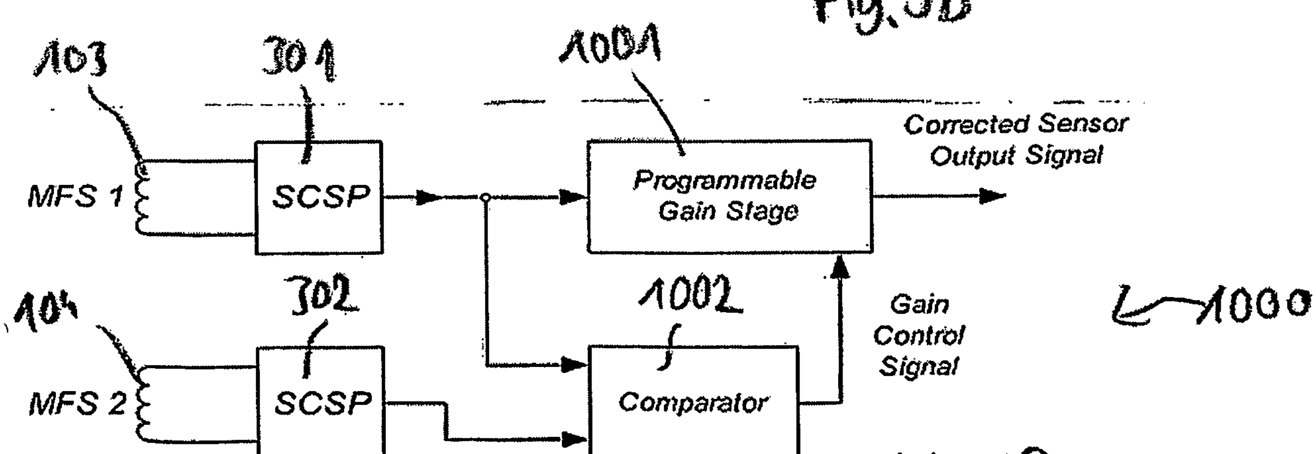


Fig. 10

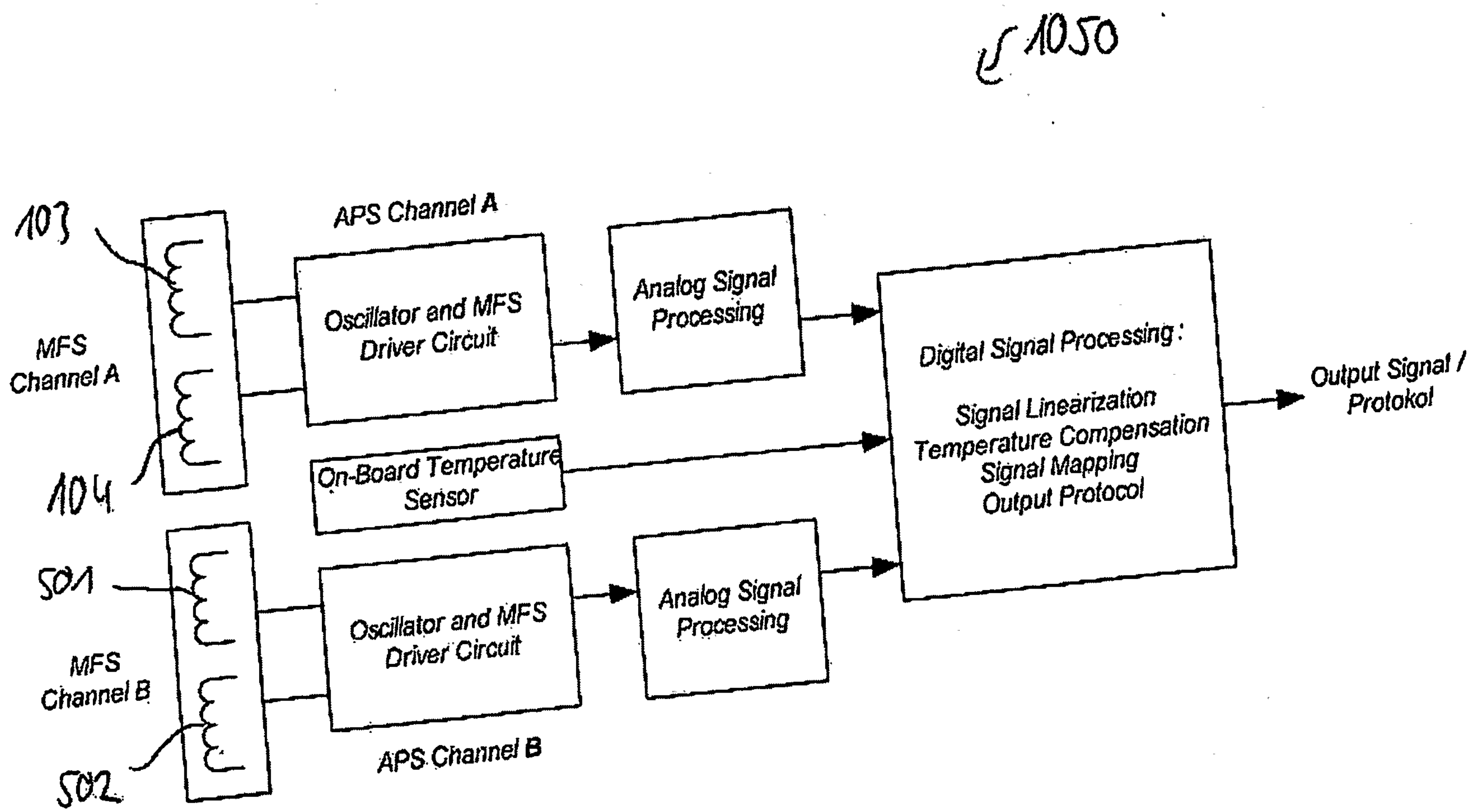

1050
103
MFS Channel A
104
501
MFS Channel B
502
APS Channel A
Oscillator and MFS Driver Circuit
On-Board Temperature Sensor
Oscillator and MFS Driver Circuit
APS Channel B
Analog Signal Processing
Analog Signal Processing
Digital Signal Processing:
Signal Linearization
Temperature Compensation
Signal Mapping
Output Protocol
Output Signal / Protokol

Fig. 10B

Specification	**Description**	**Unit**	**Value**
Max axial measurement range	*Depending on SH cross section*	*mm*	*2 to 45*
Measurement resolution	*In relation to FS (Full Scale)*	*%*	*0.1*
Analog output signal range	*APS output signal, excluding digital processing.*	*V*	*0.2 to 4.8*
Operating temperature range Of the sensing element	*PCME encoding on round SH*	*C^0*	*-50 to + 210*
Operating temperature range of the SCSP electronics		*C^0*	*-50 to +130*
Power supply current consumption	*Single channel, excluding digital*	*mA*	*<10*

Fig. 10C

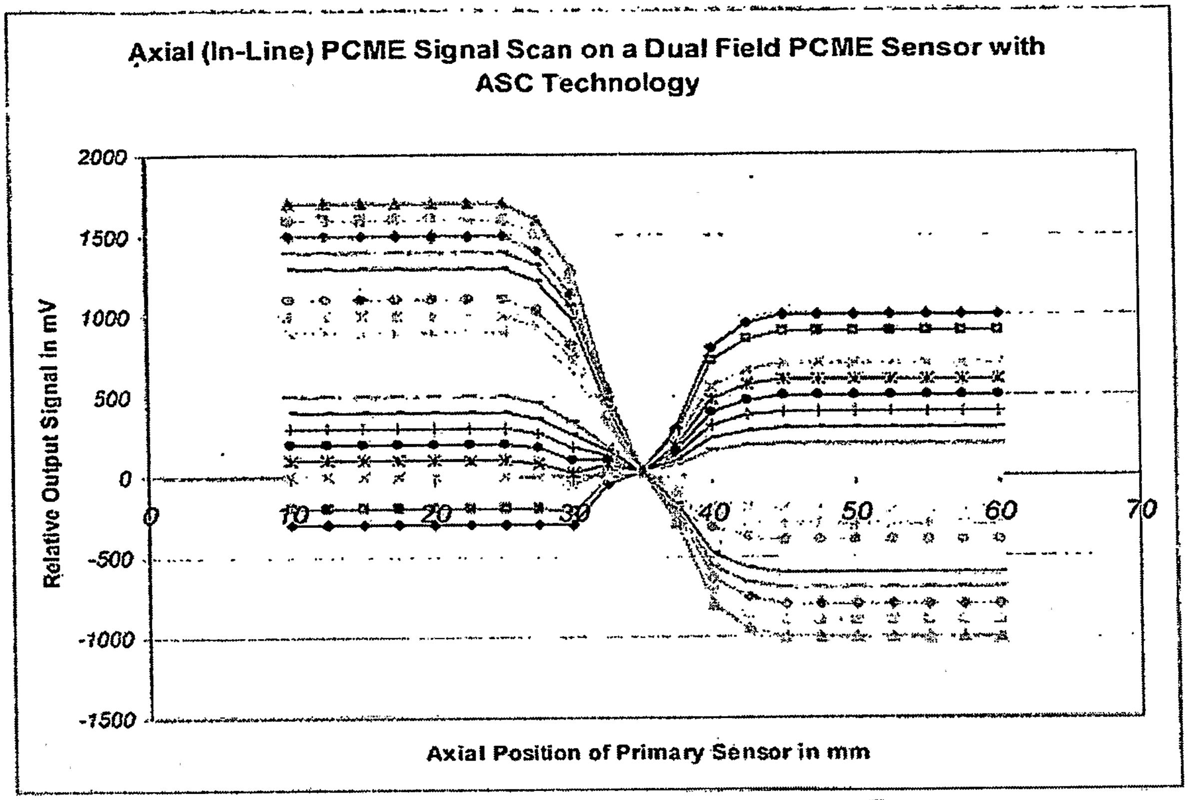


Fig. 11A

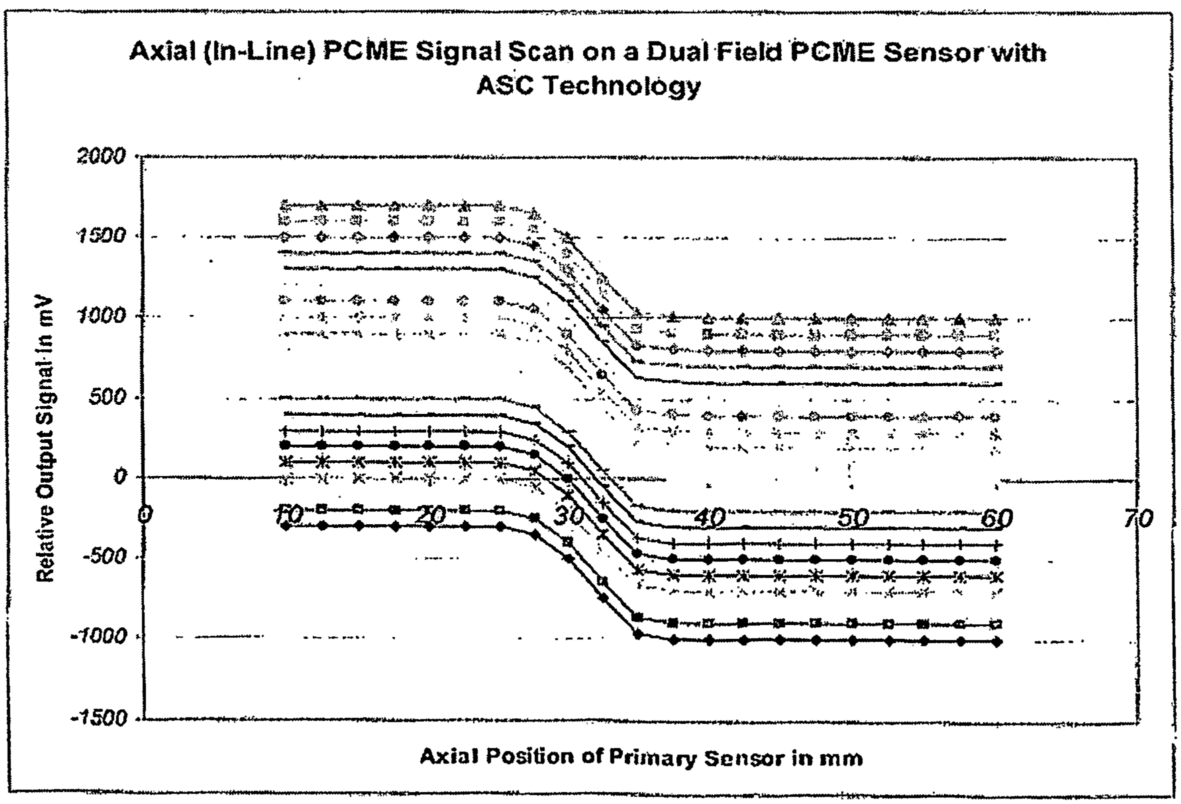


Fig. 11B

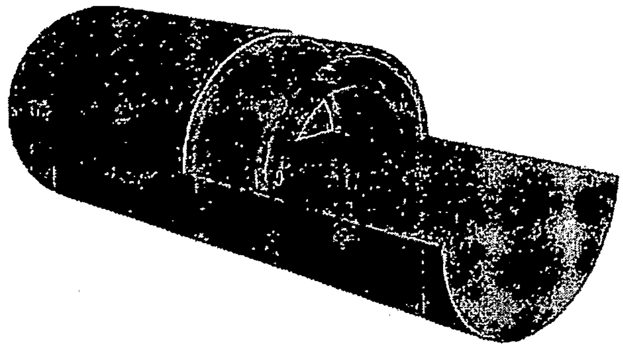


Fig. 12

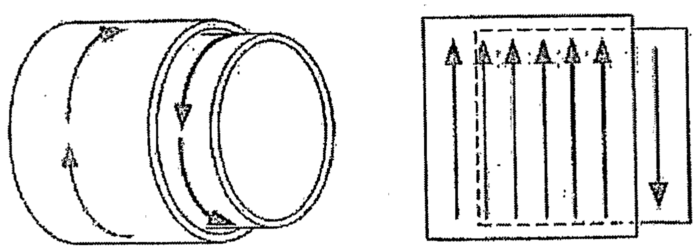


Fig. 13

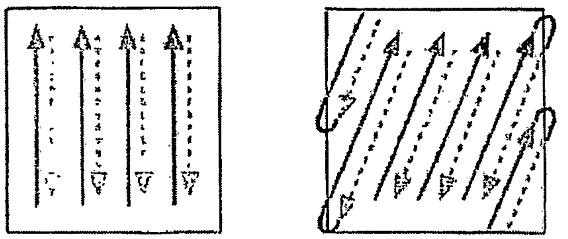


Fig. 14

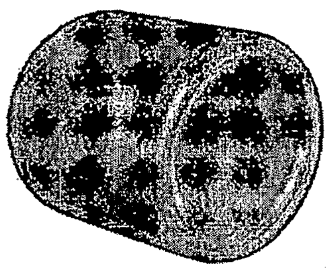


Fig. 15

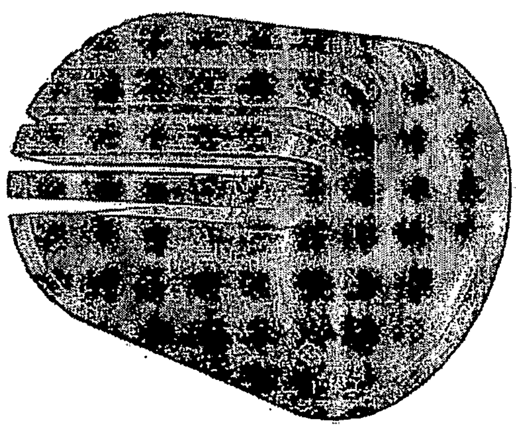


Fig. 16

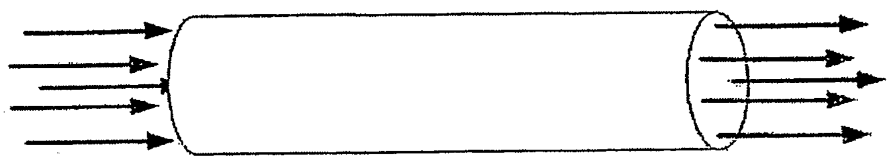


Fig. 17

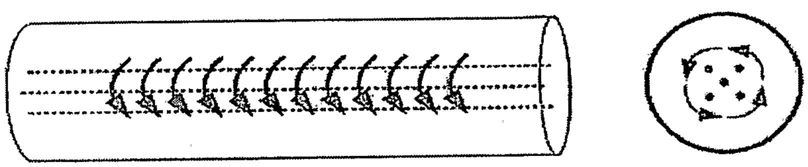


Fig. 18

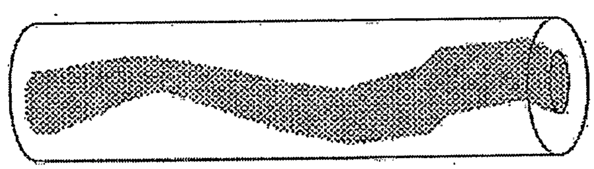


Fig. 19

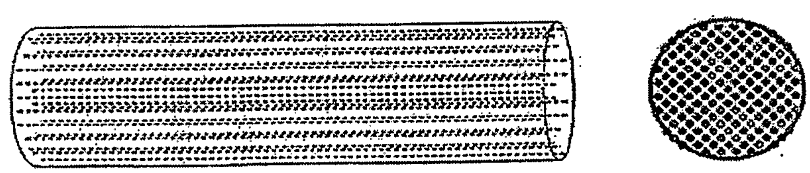


Fig. 20

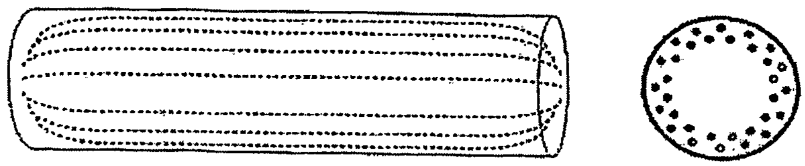


Fig.21

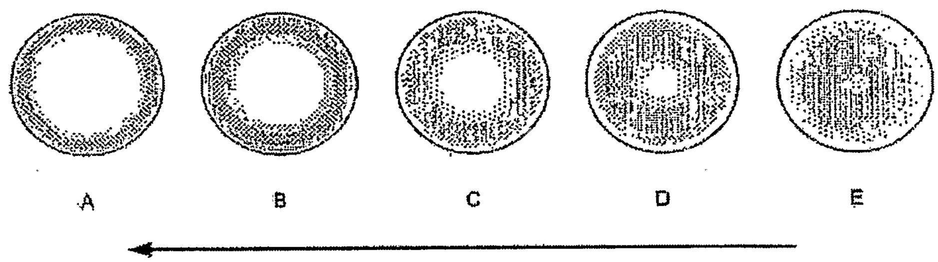


Fig.22

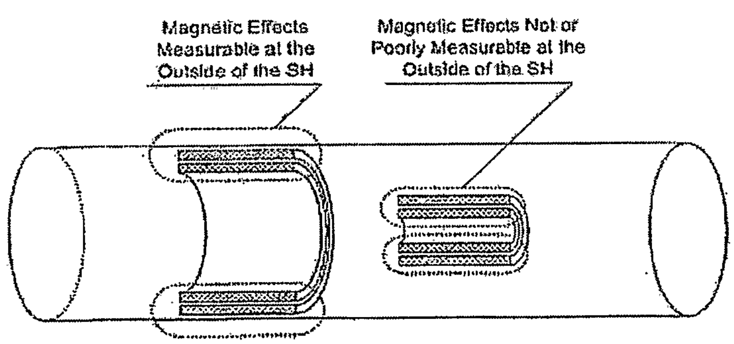


Fig.23

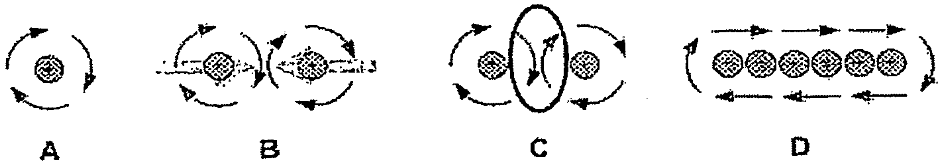


Fig. 24

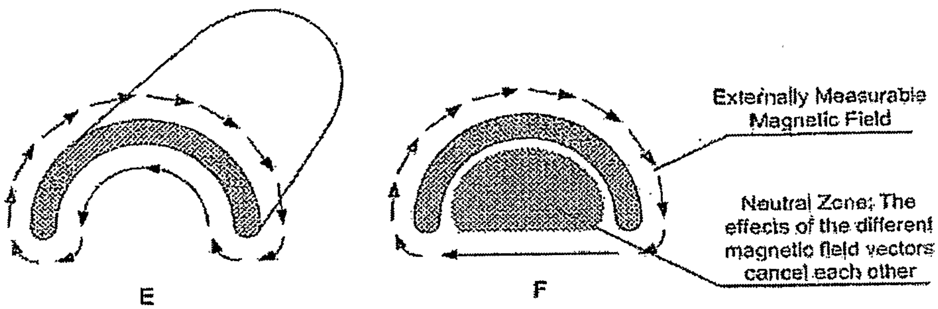


Fig. 25

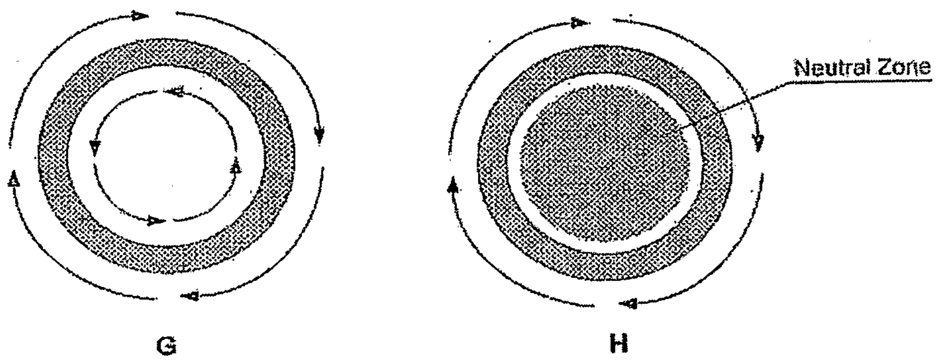


Fig. 26

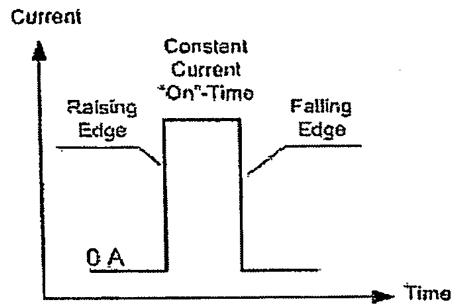

Current
Constant
Current
"On"-Time
Raising
Edge
Falling
Edge
0 A
Time

Fig. 27

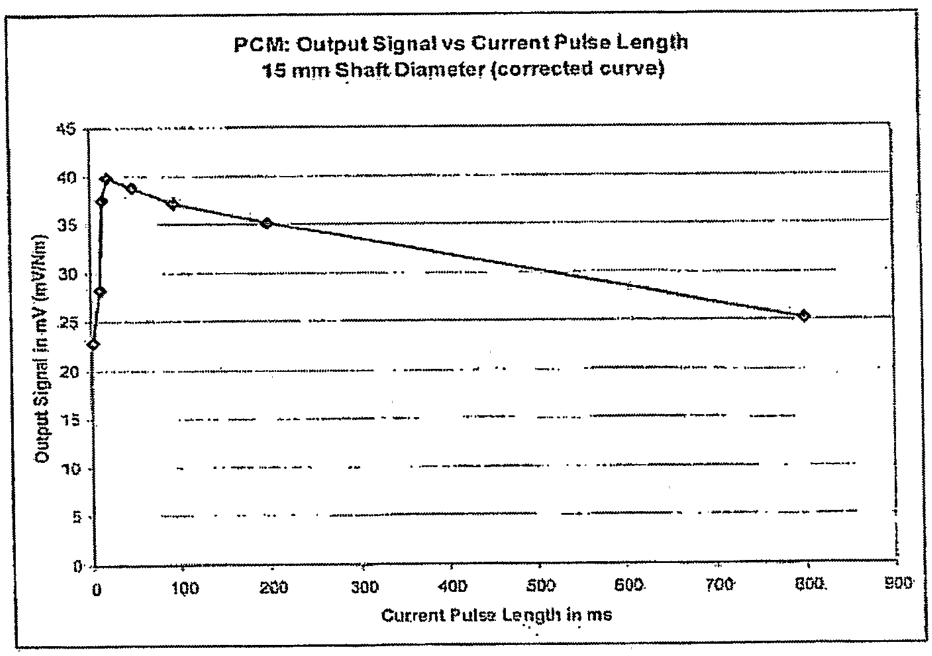

PCM: Output Signal vs Current Pulse Length
15 mm Shaft Diameter (corrected curve)
45
40
35
30
25
20
15
10
5
0
Output Signal in mV (mV/Nm)
0
100
200
300
400
500
600
700
800
900
Current Pulse Length in ms

Fig. 28

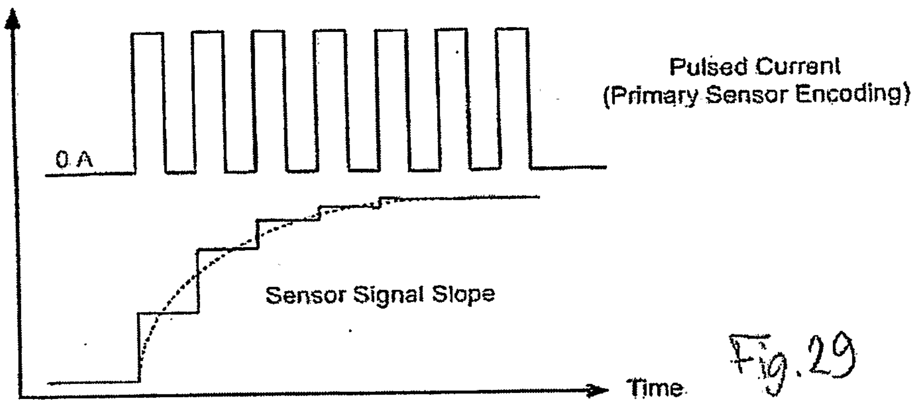


Fig.29

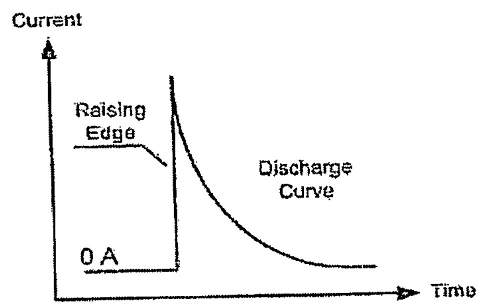


Fig.30

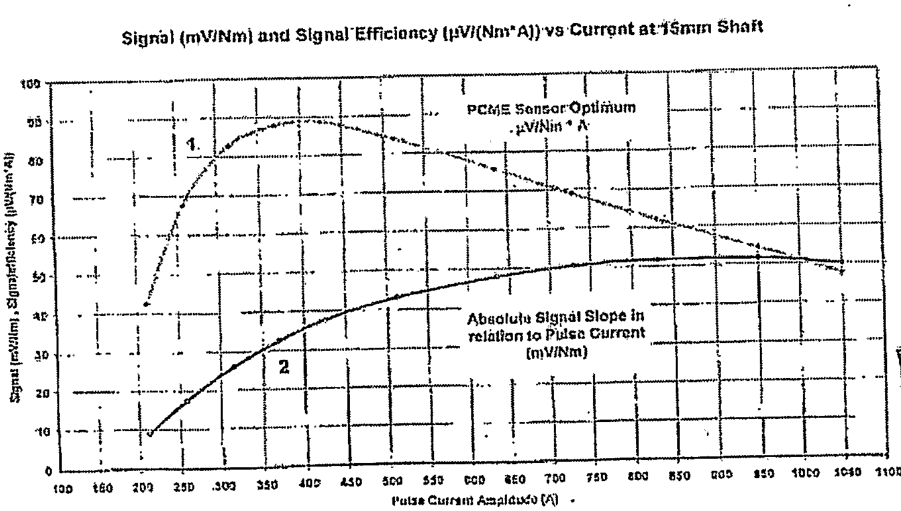


Fig.31

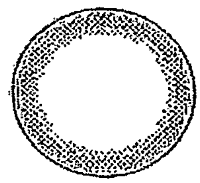


Fig. 32

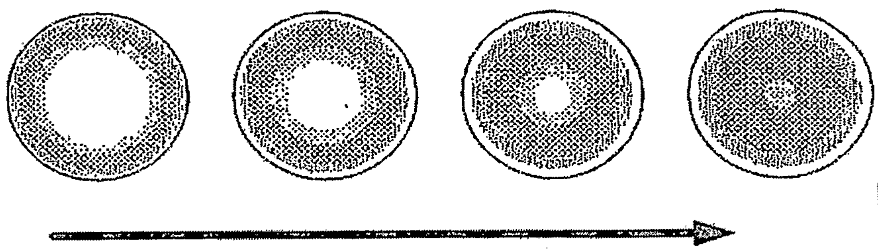


Fig 33

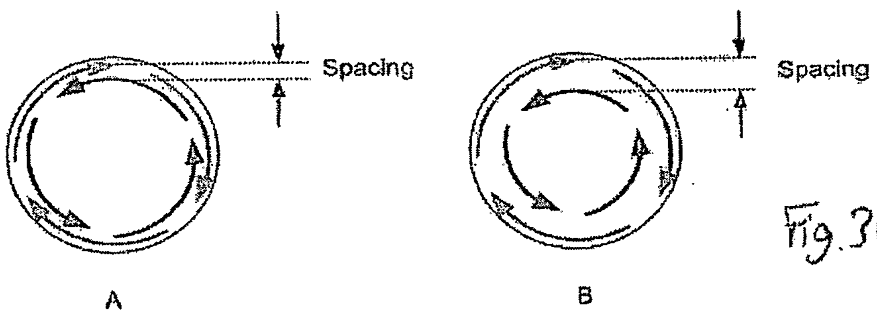


Fig. 34

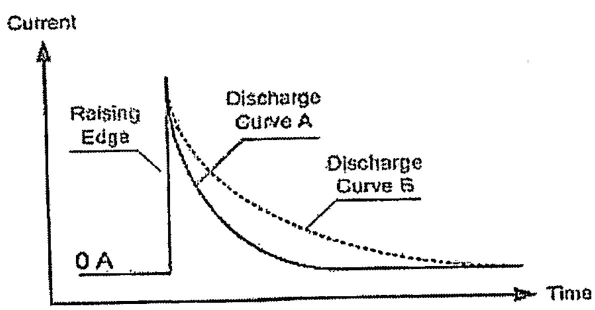


Fig. 35

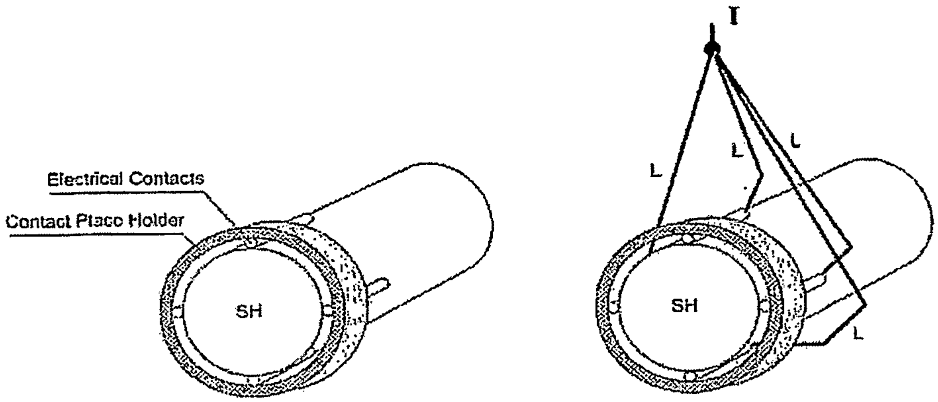


Fig 36

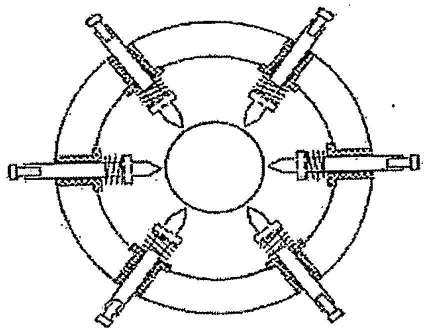


Fig 37

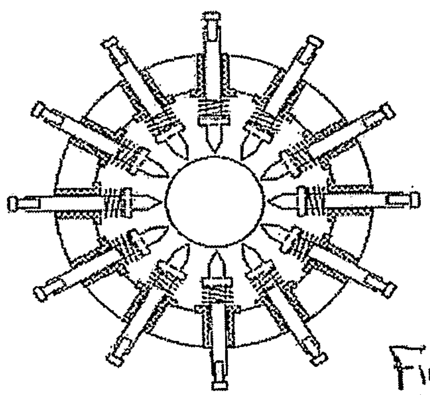


Fig 38

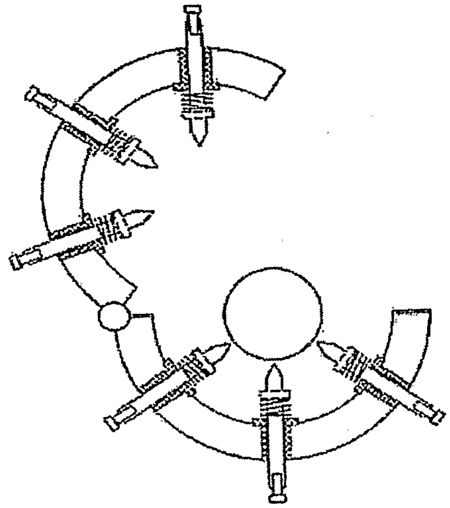


Fig 39

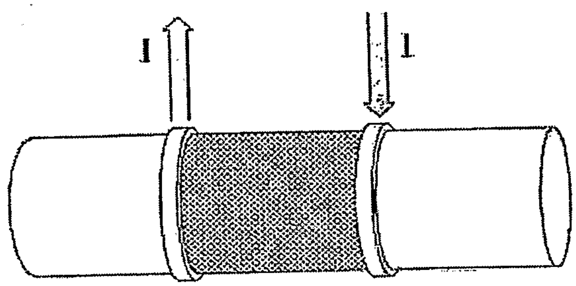


Fig. 40

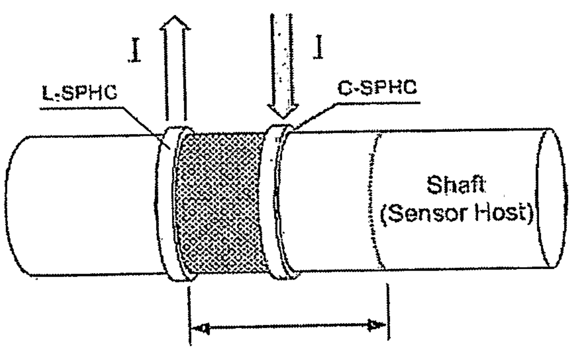


Fig. 41

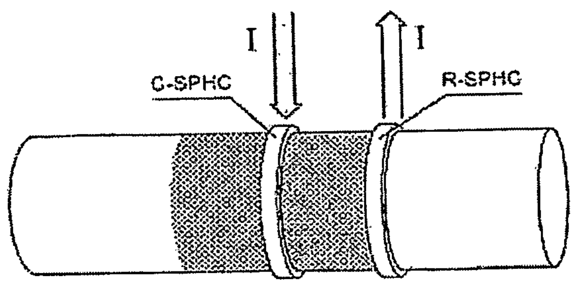


Fig 42

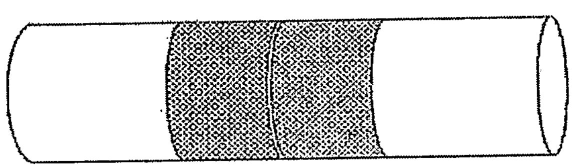


Fig 43

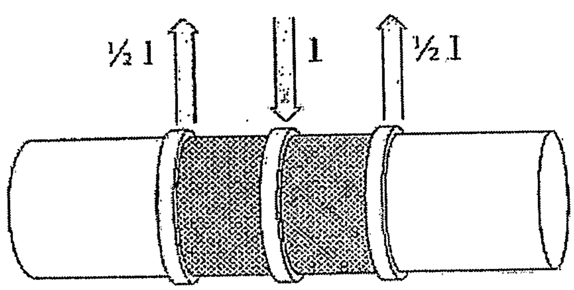


Fig. 44

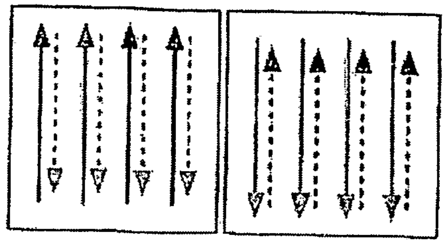


Fig. 45

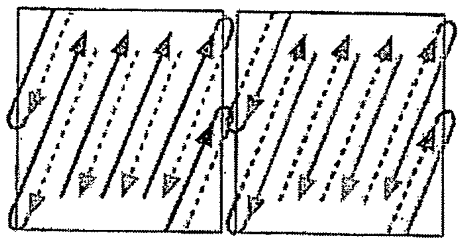


Fig. 46

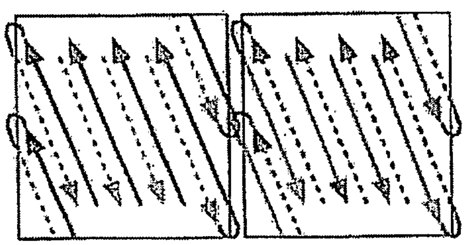


Fig. 47

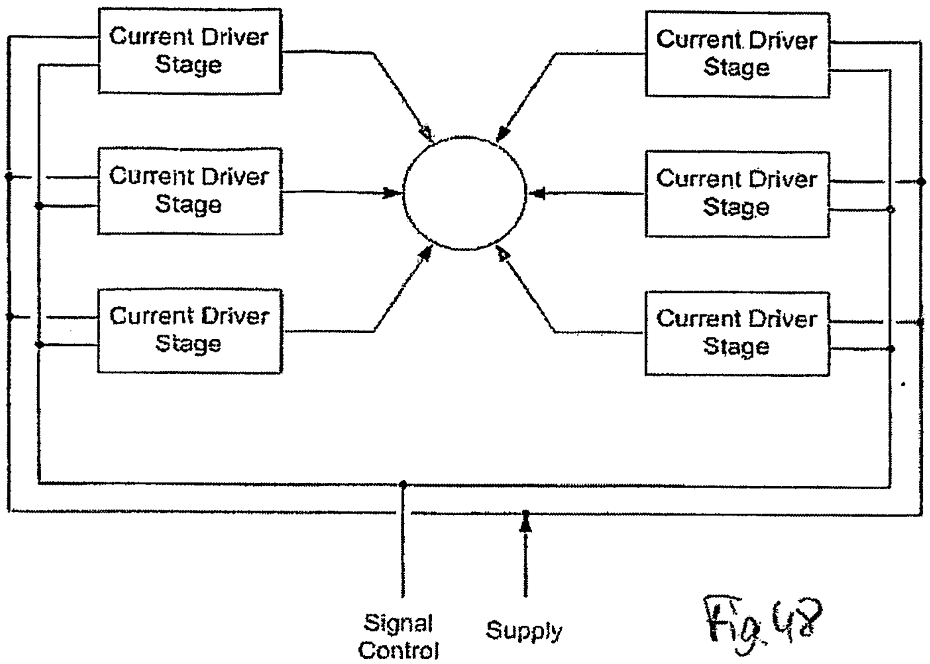

Current Driver Stage
Current Driver Stage
Current Driver Stage
Current Driver Stage
Current Driver Stage
Current Driver Stage
Signal Control
Supply

Fig. 48

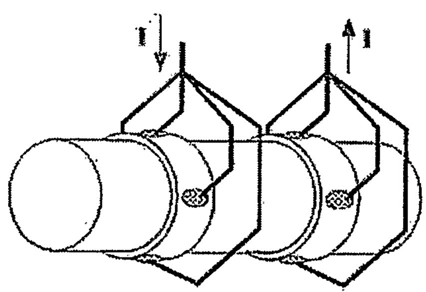

I
I

Fig. 49

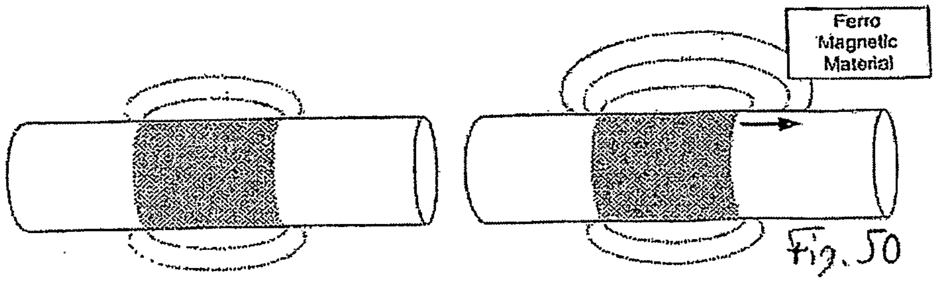


Fig. 50

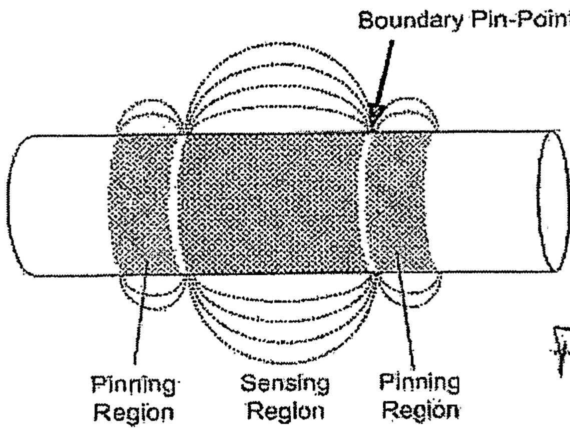


Fig. 51

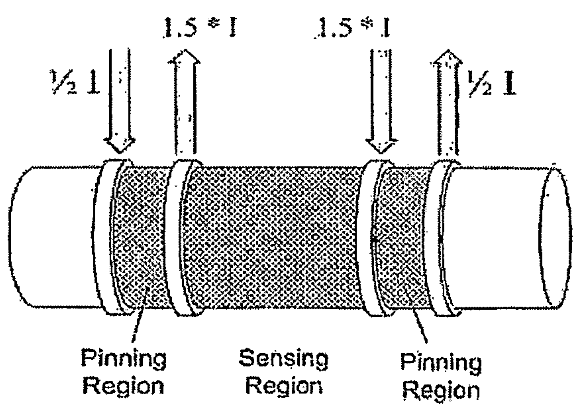


Fig. 52

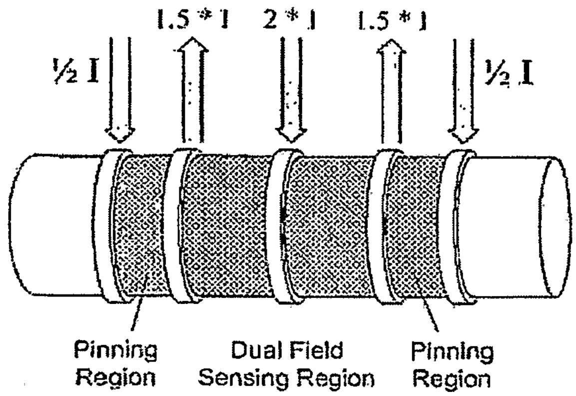


Fig. 53

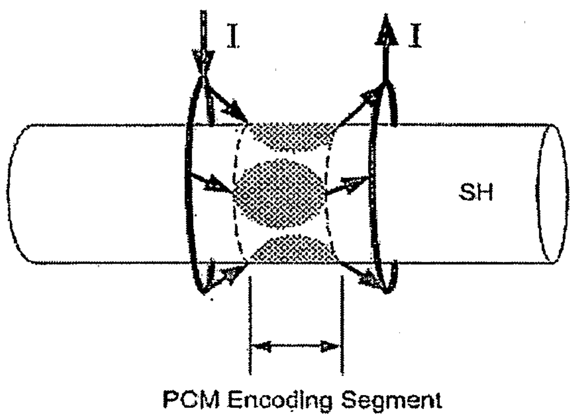


Fig. 54

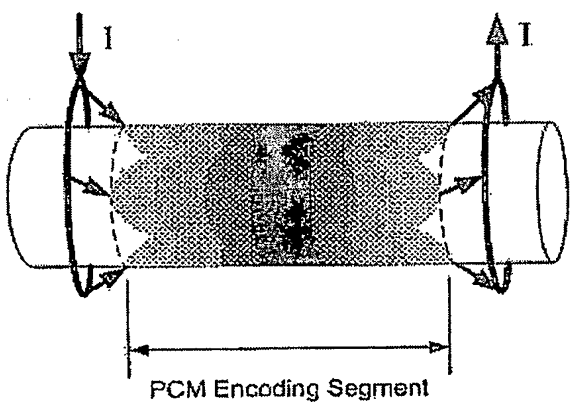


Fig. 55

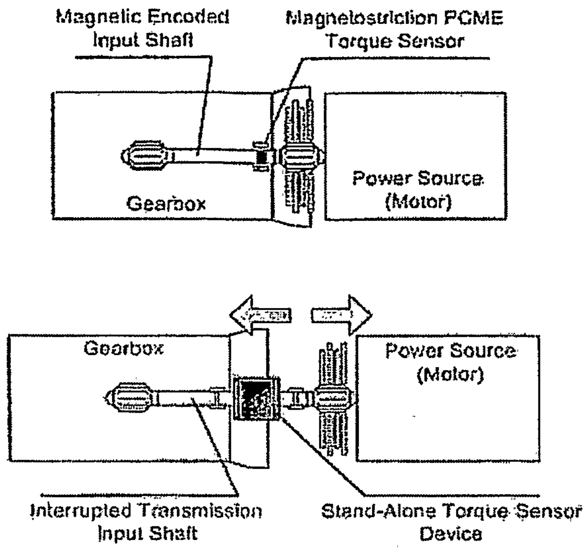

Magnetic Encoded
Input Shaft
Magnetostriction PCME
Torque Sensor
Gearbox
Power Source
(Motor)
Gearbox
Power Source
(Motor)
Interrupted Transmission
Input Shaft
Stand-Alone Torque Sensor
Device

Fig. 56

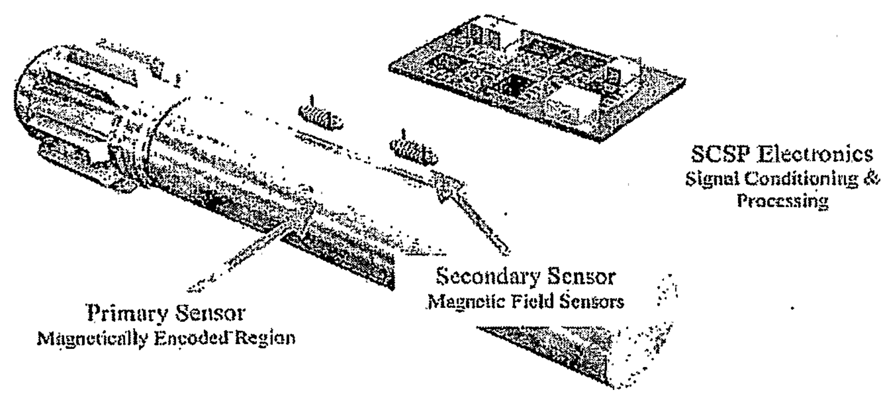

SCSP Electronics
Signal Conditioning &
Processing
Secondary Sensor
Magnetic Field Sensors
Primary Sensor
Magnetically Encoded Region

Fig. 57

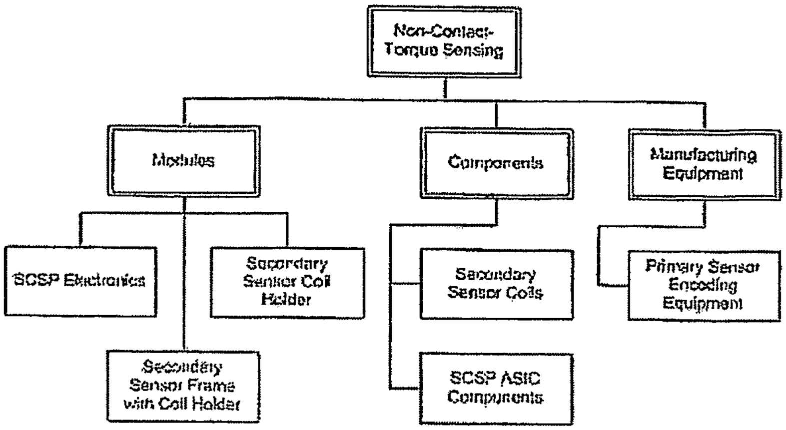


Fig. 58

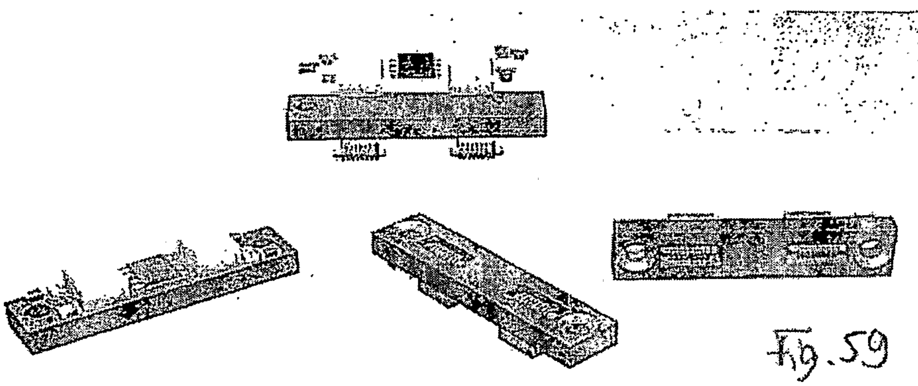


Fig. 59

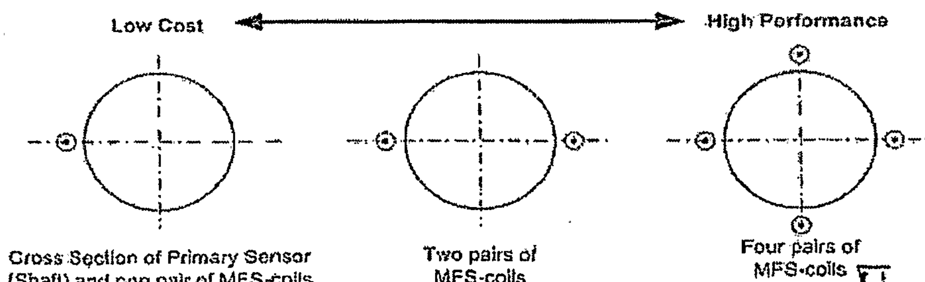


Fig. 60

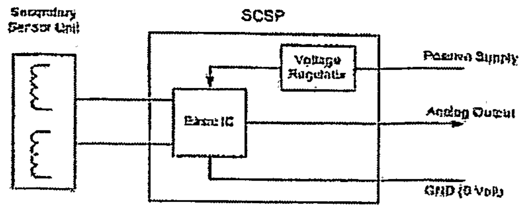

Secondary Sensor Unit
SCSP
Voltage Regulator
Positive Supply
Basic IC
Analog Output
GND (0 Volt)

Fig 61

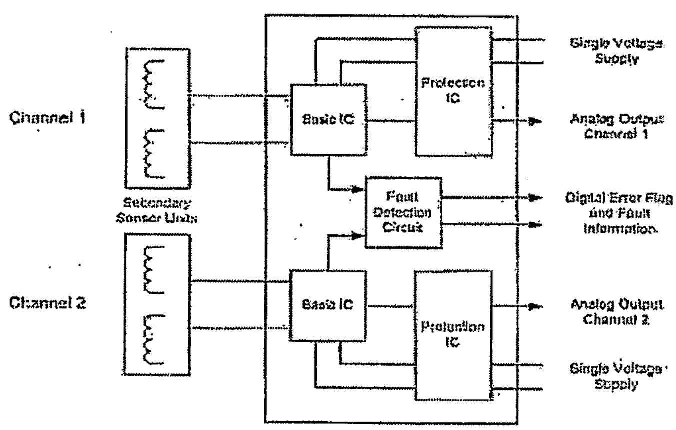
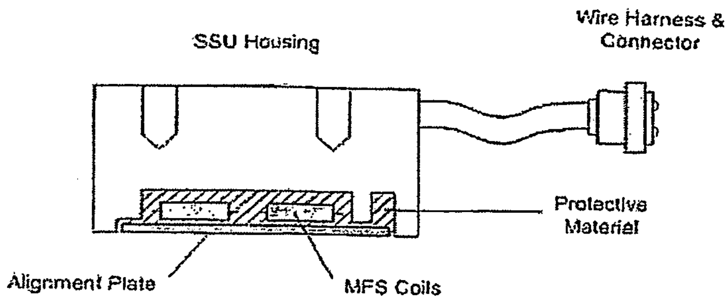
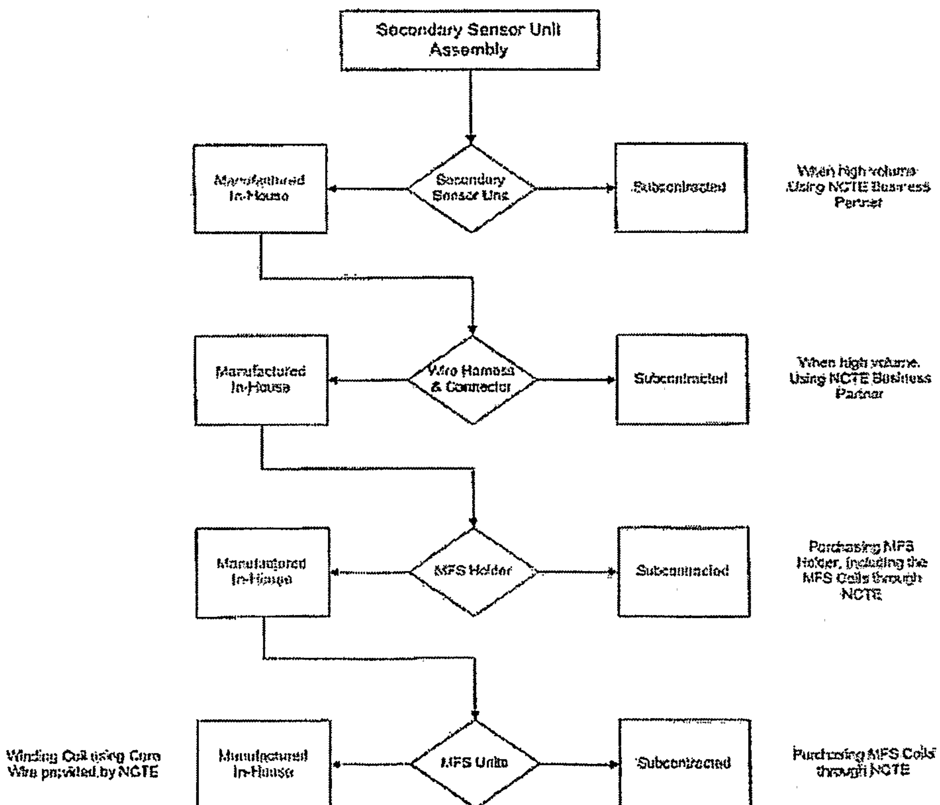

Channel 1
Channel 2
Secondary Sensor Units
Basic IC
Protection IC
Fault Detection Circuit
Single Voltage Supply
Analog Output Channel 1
Digital Error Flag and Fault Information
Analog Output Channel 2
Single Voltage Supply

Fig. 62



SSU Housing
Wire Harness & Connector
Protective Material
Alignment Plate
MFS Coils

Fig. 63



Secondary Sensor Unit Assembly
Manufactured In-House
Secondary Sensor Unit
Subcontracted
When high volume Using NCTE Business Partner
Manufactured In-House
Wire Harness & Connector
Subcontracted
When high volume. Using NCTE Business Partner
Manufactured In-House
MFS Holder
Subcontracted
Purchasing MFS Holder, including the MFS Coils through NCTE
Winding Coil using Core Wire provided by NCTE
Manufactured In-House
MFS Units
Subcontracted
Purchasing MFS Coils through NCTE

Fig. 64

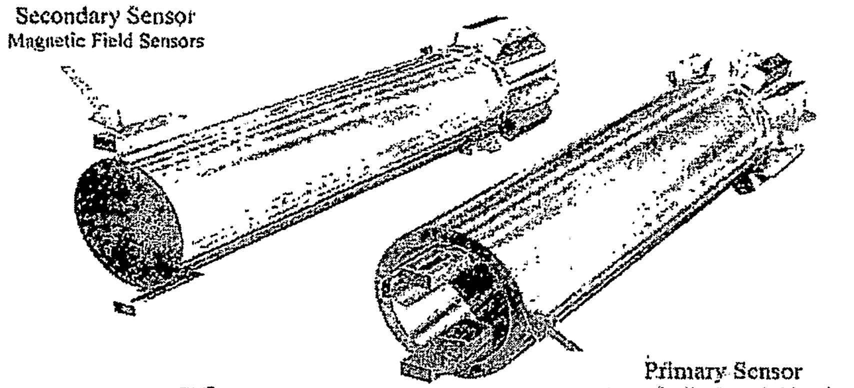

Secondary Sensor
Magnetic Field Sensors
Primary Sensor
Magnetically Encoded Region

Fig. 65

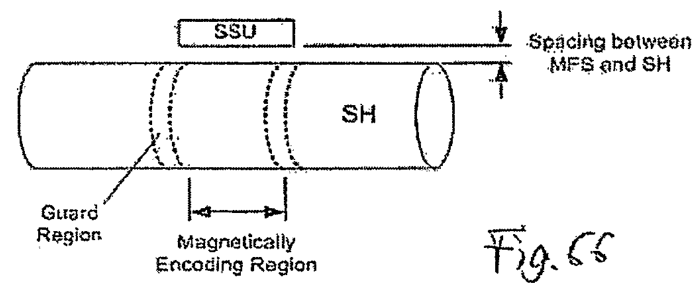

SSU
Spacing between
MFS and SH
SH
Guard
Region
Magnetically
Encoding Region

Fig. 66

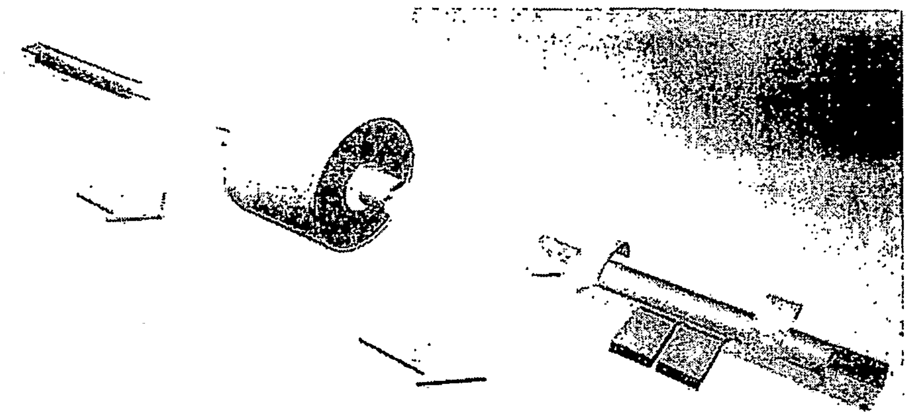


Fig. 67

Document made available under the Patent Cooperation Treaty (PCT)

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International filing date: 29 December 2004 (29.12.2004)

Document type: Certified copy of priority document

Document details: Country/Office: US
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Filing date: 09 November 2004 (09.11.2004)

Date of receipt at the International Bureau: 07 March 2005 (07.03.2005)

Remark: Priority document submitted or transmitted to the International Bureau in compliance with Rule 17.1(a) or (b)

PCT/EP2004/014797

25.02.05

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APPLICATION NUMBER: ***60/626,359***
FILING DATE: ***November 09, 2004***

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20427 U.S. PTO

[40124/04101

17513 U.S. PTO 60/626359 110904

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Inventor(s)	:	**Lutz MAY** **Wolfratshauser Str. 23a** **82578 Geretsried-Gelting** **Germany** **Citizenship: Germany**
Serial No.	:	**To Be Assigned**
Filing Date	:	**Herewith**
For	:	**A METHOD AND AN APPARATUS FOR MAGNETIZING AN OBJECT, A METHOD AND AN APPARATUS FOR CALIBRATING A FORCE AND TORQUE SENSOR DEVICE, A USE OF AN APPARATUS FOR MAGNETIZING AN OBJECT IN PARTICULAR TECHNICAL FIELDS, AND USE OF AN APPARATUS FOR CALIBRATING A FORCE AND TORQUE SENSOR DEVICE IN PARTICULAR TECHNICAL FIELDS**

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Please associate this application (Attorney Docket No. 40124/04101) with Customer No. 30636

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Name: Patrick J. Fay, Reg. No. 35,508

Signature

U.S. PROVISIONAL APPLICATION REQUEST TRANSMITTAL

Enclosed herewith please find the following:

1. 1 sheet of Title Page and 69 sheets of Specification.
2. 34 sheets of drawings.
3. Return Receipt Postcard.

A check in the amount of **$160.00** is enclosed herewith. The Commissioner is hereby authorized to charge the Deposit Account of **Fay Kaplun & Marcin, LLP No. 50-1492** any additional fees associated with this communication or arising during the pendency of this application. A copy of this Transmittal is submitted for this purpose.

Date: November 9, 2004

By: ______________________

Patrick J. Fay (Reg. No. 35,508)

Fay Kaplun & Marcin, LLP
150 Broadway, Suite 702
New York, NY 10038
(212) 619-6000- Telephone
(212) 619-0276- facsimile

[40124/04101]

U.S. PROVISIONAL PATENT APPLICATION

For

A METHOD AND AN APPARATUS FOR MAGNETIZING AN OBJECT, A METHOD AND AN APPARATUS FOR CALIBRATING A FORCE AND TORQUE SENSOR DEVICE, A USE OF AN APPARATUS FOR MAGNETIZING AN OBJECT IN PARTICULAR TECHNICAL FIELDS, AND USE OF AN APPARATUS FOR CALIBRATING A FORCE AND TORQUE SENSOR DEVICE IN PARTICULAR TECHNICAL FIELDS

Inventor(s):

Lutz MAY

Total Pages (including title page and specification): 70

Represented by:
FAY KAPLUN & MARCIN, LLP
150 Broadway, Suite 702
New York, NY 10038
(212) 619-6000 (tel)
(212) 619-0276 (fax)
info@FKMiplaw.com

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Name: Patrick J. Fay, Reg. No. 35,508

Signature

Application No.
New Application
NCTENGINEERING GMBH

Our Reference
N 7179 / KK

Munich,
8. November 2004

NCTEngineering GmbH

Otto-Hahn-Straße 24, 85521 Ottobrunn, Deutschland

A method and an apparatus for magnetizing an object, a method and an apparatus for calibrating a force and torque sensor device, a use of an apparatus for magnetizing an object in particular technical fields, and a use of an apparatus for calibrating a force and torque sensor device in particular technical fields

---

Background of the Invention

Field of the Invention

KK:AD

The present invention relates to a method and an apparatus for magnetizing an object, to a method and an apparatus for calibrating a force and torque sensor device, to a use of an apparatus for magnetizing an object in particular technical fields, and to a use of an apparatus for calibrating a force and torque sensor device in particular technical fields.

Description of the Related Art

Magnetic transducer technology finds application in the measurement of torque and position. It has been especially developed for the non-contacting measurement of torque in a shaft or any other part being subject to torque or linear motion. A rotating or reciprocating element or an element which is subject to an axial load or to shear forces can be provided with a magnetized region, i.e. a magnetic encoded region, and when the shaft is rotated or reciprocated, such a magnetic encoded region generates a characteristic signal in a magnetic field detector (like a magnetic coil) enabling to determine torque, force or position of the shaft.

For such kind of sensors which are disclosed, for instance, in WO 02/063262, it is important to have an accurately defined magnetically encoded region which can be manufactured and calibrated with low cost.

Summary of the Invention

It is an object of the present invention to provide a sensor device having a magnetically encoded region, wherein the sensor device shall be manufacturable and operable with low cost.

This object is achieved by providing a method and an apparatus for magnetizing an object, a method and an apparatus for calibrating a force and torque sensor device, a use of an apparatus for magnetizing an object in particular technical fields, and a use of an apparatus for calibrating a force and torque sensor device in particular technical fields according to independent aspects of the invention as mentioned in the following.

In the following, different aspects of the invention will be described.

Aspects 1, 10, 28, 29, 33, and 34 are independent aspects of the invention which may be realized with or without any other means. Aspects 2 to 9 relate to preferred embodiments of aspect 1. Aspects 11 to 27 relate to preferred embodiments of aspect 10. Aspects 30 and 32 relate to preferred embodiments of aspect 29.

1. aspect: A method for magnetizing a first object and/or a second object, the method comprising the steps of

arranging a first object in such a manner that the first object encloses a second object;

applying a first electrical signal to the second object, wherein the first electrical signal is adapted such that at least a portion of the first object and/or of the second object is magnetized.

2. aspect: The method according to aspect 1,
wherein the first electrical signal is a first pulse signal or a sequence of subsequent pulse signals.

3. aspect: The method according to aspect 2,
wherein, in a time versus current diagram, the first pulse signal has a fast raising edge which is essentially vertical and has a slow falling edge.

4. aspect: The method according to any of aspects 1 to 3,
wherein the first electrical signal is a current or a voltage.

5. aspect: The method according to any of aspects 1 to 4,
wherein a second electrical signal is applied to the second object after having applied the first electrical signal, wherein the second electrical signal is adapted such that at least a portion of the first object and/or of the second object is magnetized, and wherein the second electrical signal differs from the first electrical signal concerning at least one of the group consisting of amplitude, sign, signal shape and duration.

6. aspect: The method according to aspect 5,
wherein the second electrical signal is a second pulse signal or a sequence of subsequent pulse signals.

7. aspect: The method according to aspect 6,
wherein, in a time versus current diagram, the second pulse signal has a fast raising edge which is essentially vertical and has a slow falling edge.

8. aspect: The method according to any of aspects 5 to 7,
wherein the first object and/or the second object is magnetized by applying the first electrical signal and the second electrical signal such that in a direction essentially perpendicular to a surface of the first object and/or of the second object, a magnetic field structure is generated such that there is a first magnetic flow in a first direction and a second magnetic flow in a second direction, wherein the first direction is opposite to the second direction.

9. aspect: The method according to any of aspects 5 to 8,
wherein the second electrical signal is a current or a voltage.

10. aspect: An apparatus for magnetizing a first object and/or a second object, the apparatus comprising

a first object;

a second object;

an electrical signal source;

wherein the first object is arranged in such a manner that the first object encloses the second object;

wherein the electrical signal source is adapted to apply a first electrical signal to the second object, wherein the first electrical signal is adapted such that at least a portion of the first object and/or of the second object is magnetized.

11. aspect: The apparatus according to aspect 10,
wherein the first object is a hollow tube.

12. aspect: The apparatus according to aspect 10 or 11,
wherein the second object is one of the group consisting of a shaft, a wire and a hollow tube.

13. aspect: The apparatus according to any of aspects 10 to 12,
wherein the second object is arranged at a center of the first object.

14. aspect: The apparatus according to any of aspects 10 to 13,
wherein the electrical signal source comprises a capacitor bank.

15. aspect: The apparatus according to any of aspects 10 to 14,
wherein the first object has a first electrical connection and has a second electrical connection, wherein the second object has a first electrical connection and has a second electrical connection, and wherein the second electrical connection of the first object is coupled to the first electrical connection of the second object.

16. aspect: The apparatus according to aspect 15,
wherein the electrical signal source is connected such that a first electrical signal is applyable between the first electrical connection of the first object and the second electrical connection of the second object.

17. aspect: The apparatus according to aspect 15,
wherein the first object has a third electrical connection, wherein the second object has a third electrical connection.

18. aspect: The apparatus according to aspect 17,
wherein the electrical signal source is connected such that a first electrical signal is applyable between the first electrical connection of the first object and the second electrical connection of the second object, and such that a second electrical signal is applyable between the third electrical connection of the first object and the third electrical connection of the second object.

19. aspect: The apparatus according to any of aspects 15 to 18,
further comprising an electrically conductive coupling element arranged to couple the second electrical connection of the first object to the first electrical connection of the second object.

20. aspect: The apparatus according to aspect 19,
wherein the coupling element is an electrically conductive plate or an electrically conducting liquid.

21. aspect: The apparatus according to any of aspects 10 to 20,
wherein the second object, in addition to the first object, is adapted to be magnetized when the first electrical signal is applied.

22. aspect: The apparatus according to any of aspects 10 to 14,
wherein the second object comprises a first connection and a second connection, wherein the electrical signal source is connected between the first connection and the second connection of the second object.

23. aspect: The apparatus according to any of aspects 10 to 14, or 22,
wherein the electrical signal source is disconnected from the first object.

24. aspect: The apparatus according to aspect 22 or 23,
wherein a portion of the second object is free from an enclosure with the first object, further comprising a shielding element which is arranged and adapted to electromagnetically shield the portion of the second object being free from an enclosure with the first object from the first object.

25. aspect: The apparatus according to aspect 24,
wherein the shielding element is arranged between the first element and the portion of the second object being free from an enclosure with the first object.

26. aspect: The apparatus according to aspect 24,
wherein the shielding element is a tube which is arranged to enclose the portion of the second object being free from an enclosure with the first object.

27. aspect: The apparatus according to aspect 24,
wherein the shielding element comprises a plurality of sub-elements which are arranged surrounding the portion of the second object being free from an enclosure with the first object.

28. aspect: A method for calibrating a force and torque sensor device, the method comprising the steps of

providing a force and torque sensor device having a magnetically encoded region on an object and a magnetic field detector adapted to detect a signal resulting from a force or a torque applied to the object;

applying a pre-known force to the object;

detecting a signal resulting from the pre-known force applied to the object;

calibrating the force and torque sensor device based on a correlation between the pre-known force and the detected signal resulting from the pre-known force.

29. aspect: An apparatus for calibrating a force and torque sensor device, the apparatus comprising

a force and torque sensor device;

a pre-known force generating element;

a calibrating unit;

wherein the force and torque sensor device has a magnetically encoded region on an object and a magnetic field detector adapted to detect a signal resulting from a force or a torque applied to the object;

wherein the pre-known force generating element is adapted to apply a pre-known force to the object;

wherein the calibrating unit is adapted to calibrate the force and torque sensor device based on a correlation between a pre-known force and a detected signal resulting from the pre-known force.

30. aspect: The apparatus according to claim 29,
wherein the pre-known force generating element is a pre-known weight.

31. aspect: The apparatus according to claim 29,
wherein the pre-known force generating element is adapted to apply a pre-known shear stress.

32. aspect: The apparatus according to claim 29,
wherein the pre-known force generating element is a pre-known torque.

33. aspect: Using an apparatus according to any of aspects 10 to 27 for magnetizing one of the group consisting of a mining shaft, a concrete processing cylinder, a push-pull rod in a gearbox, and a shaft of an engine.

34. aspect: Using an apparatus according to any of aspects 29 to 32 for calibrating a force and torque sensor device of the group consisting of a mining shaft, a concrete processing cylinder, a push-pull rod in a gearbox, and a shaft of an engine.

In the following, the above mentioned independent aspects of the invention will be described in more detail.

Within this specification, the expression "magnetizing" particularly has the meaning that microscopic or elementary magnets like magnetic moments, grains or domains which are present within a magnetizable material are treated such that at least a part of them becomes aligned along a particular direction, so that a random magnetic orientation is at least partially removed.

The method for magnetizing a first object and the apparatus for magnetizing a first object according to the independent aspects mentioned above have the advantage that a first object can be magnetized by applying an electrical signal to a second object which is surrounded by the first object. For instance, a wire or a shaft or a rod as the second element can be surrounded by a hollow cylinder as the first object. Applying an appropriate electrical signal to the second object then allows to generate a magnetized region in the first object due to a physical effect which is similar like the physical effects occurring in the case of a transformator. In other words, a time-dependent electrical signal, like a current pulse, flowing

through the second object generates a magnetic field which influences magnetizable material of the first object in such a manner that it becomes magnetized. The magnetization scheme of the invention allows a cheap and easy magnetization even of large hollow cylinders – as they occur particularly in the field of mining and drilling equipment. Thus, a magnetically encoded region can be formed in an already existing industrial steel hollow cylinder or tube. This allows that also already existing magnetizable objects, for instance a drilling shaft, may be provided with a magnetically encoded region so that a torque, a bending force and an axial load applied to such an object can be measured by a simple magnetic field detector like a coil arranged adjacent to the magnetized object.

According to the described embodiment, particularly the outer first object is magnetized. However, in case that also the inner second object is made of a magnetizable material, the second object is magnetized simultaneously.

Another advantage related to the method and the apparatus for magnetizing a second object according to the independent aspects of the invention is the opportunity to connect the first object to the second object at a selected position, for instance at an end portion of the first object and at an end portion of the second object. According to such an architecture, the current flowing through the second object is injected also in the first object to form a counter magnetic field there, which stabilizes the current distribution in the objects. Thus, a high quality magnetically encoded region may be formed in the second object, yielding a sensor with more reproducible and reliable properties.

According to the described embodiment, particularly the inner second object is magnetized. However, in case that also the outer first object is made of a magnetizable material, the first object is magnetized simultaneously.

In the following, the method and the apparatus for calibrating a force and torque sensor device will be explained. An important idea of this calibrating method is to simply apply a pre-known calibrating force, for instance a known mass or weight, to an object having a magnetically encoded region (which may be generated, for instance, according to the method of the invention of magnetizing an object). Such a weight or gravity force applied to a torque and force sensor results in a magnetic signal which can be detected by a magnetic field detector arranged in the vicinity of the magnetically encoded region. Therefore, the correlated data pair of the applied force and the resulting detection signal of the magnetic field detector can be stored. The magnetically encoded region can be encoded, for instance, according to the above described method of magnetizing an object, or to the technology mentioned in WO 02/063262, or according to the so-called PCME technology which will be described below in detail.

The thus measured correlation between an axial load and a detected signal of the magnetic field detector can then be used for a calibration of the sensor. When the object calibrated in this manner is practically used (for instance as a drilling shaft), a measured detection signal can be associated with an corresponding axial load force, using the calibration data pair estimated using the known mass. It is also possible, during calibration, to measure a plurality of calibration data pairs to refine the calibration.

Further, the data pair of a known axial load and a corresponding detecting signal may also serve as an calibration information which may be used with a sensor which is subject of an applied torque during practical use. In other words, an axial load calibration calibrates a torque sensor. This aspect is particularly advantageous in an application in which a very heavy object is used, for example in the context of a drilling shaft in a mining application, when the torque applied to such a drilling shaft shall be measured. In this case, it is very easy just to place the drilling shaft, for example a tube, on a stable ground base and to put a known mass element on the upper end of the drilling shaft. In contrast to this, it would be very

difficult to apply a calibration torque to such a drilling shaft for calibrating a torque sensor. It is easier to calibrate a torque sensor by using a calibrating axial force.

According to further independent aspects of the invention, the methods and apparatuses mentioned above may be implemented in the frame of a mining shaft, a concrete processing cylinder, a push-pull rod in a gearbox, or a shaft of an engine. In all of these applications, the magnetization and the calibration of such a torque, force and position sensor is highly advantageous, since it allows to manufacture a highly accurate and reliably calibrated force, position and torque sensor with low costs. Particularly, mining and drilling equipment may be provided with the systems of the invention, and may be used for monitoring a drilling direction and drilling forces. Further applications of the invention are the recognition and the analysis of engine knocking.

Thus, a real-time measurement of actual mechanical forces applied and being effective "on the job" of large mining and drilling equipment is enabled according to the invention. The harsh outdoor conditions and dealing with abrasive materials is something traditional sensing technologies have difficulties to deal with, whereas the systems of the invention are compatible with such conditions without any problems. Mechanical forces which may be measured according to the invention are torque, bending, axial load and potential mining equipment overloads.

By the magnetization method of the invention, a unique power-shaft encoding process is employed which allows utilizing the magnetic properties of many types of industrial steel so that a standard drilling shaft turns into a high precision force sensor. The actual time required to apply the encoding process is a fraction of a second and is permanent. After the desired section of the drilling shaft has been treated with the process of the invention, this part of the shaft is emanating a specific signal in relation to the applied mechanical forces to the shaft. This signal can be detected, for instance, by a passive electrical component that is placed

several millimetres away from the shaft surface. Nothing needs to be attached to the shaft and nothing needs to touch the shaft, therefore the mean time between failure is very high (i.e. the invention provides a very reliable sensing solution). This non-contact mechanical force measurement principle relies only on the ferromagnetic properties of the drilling or power-transmitting shaft. It provides real-time information of any mechanical force that is travelling through the encoded section of the shaft, including rotational torque, bending forces, shearing forces and axial push-pull load. The overall signal bandwidth of the force-sensing technology is, according to an embodiment, 29kHz or around 100,000 measurement samples per second. In addition, a distinct signal will be emitted when the drilling shaft has been exposed to mechanical overload and is about to fail.

In large equipment it is often the case that the mechanical forces do not travel symmetrically or even distributed through the power or drilling shaft. Therefore, the magnetic field detector preferably "looks" at several critical locations at the shaft to get a larger picture. However, particularly in statically operating equipment (where the shaft does not rotate) it is often recommendable to work with one magnetic detecting device only.

The sensor of the invention can operate under water, in oil, or even in very dusty environment (like in concrete pumps or concrete mixing stations). The sensor can withstand temperatures in a very large range, particularly from –50°C to +210°C.

The sensor signal detection units may be connected to a custom specific electronic circuit that can be placed several metres away from the magnetic field detectors itself. Only two wires ("twisted pair") may be implemented to connect a magnetic field detector with a corresponding electronic circuit. The output signal of such an electronic circuit can be a buffered analogue +5V signal, whereby +2500V may equal to zero torque. The overall electrical current consumption for a torque, axial load, or bending sensor is less than 5 mA per sensor channel.

The magnetic field detectors may be placed outside or inside a magnetically encoded hollow shaft. Assuming that mechanical forces transmitted through such a shaft are not passing through the magnetically encoded section symmetrically, several magnetic field detectors may be placed geometrically around the shaft to be able to capture a highly resolved "force picture".

The encoding of large drilling shafts may be done "at site" to eliminate the potential need of shipping the heavy shaft to a specific factory location. The encoding equipment may be portable/mobile and can be used under almost all weather conditions. Under ideal circumstances, the drilling shaft can be placed on its own onto the ground for the encoding process. However, under the correct circumstances, the drilling shaft can be encoded while still placed in the drilling or mining equipment. This is particularly possible if the shaft can be accessed and is not hidden away. Such a mobile magnetizing and calibration unit can be brought very close to a drilling shaft.

An important feature of the sensing technology according to the invention is the way the permanent encoding drilling shaft may be calibrated. In case of a one meter diameter drilling shaft which is capable to deal with one million Nm torque, it will be normally be difficult to apply a "beam and weight" method for the shaft torque sensor calibration. When placing upright on a horizontal and structurally sound surface, the measurement performances of the magnetically encoded shaft can be defined within a relative short time by relying on the way the "permanently" embedded signal source is behaving. This is particularly of interest when the drilling equipment has to be serviced and maintained at remote and difficult to reach locations.

The mechanical force sensing technology according to the invention can be implemented in large-scale oil drilling equipment to detect the direction the drilling head is moving, and to

measure the drilling pipes axial load (forward thrust) at the drilling heads location. In this application, the entire sensor system may be exposed to pressures of >1,500 bars and to temperatures >200°C. In another application, the sensing principle is measuring the mechanical forces applied to large-scale mobile/moving cranes. Here, the magnetically encoded sensor has the task to prevent the crane from falling (falling over or tilting) when critical load situations occur. Other applications of the invention are wind power plants, large extruder equipment, abrasive material pumping station, and large-scale industrial gear box systems.

It is mentioned that – as an alternative to the first independent aspect - a second object (e.g. a shaft) enclosed by a first object (e.g. a hollow tube) can be magnetized by applying an electrical signal to the first object. This aspect is related to a method for magnetizing a second object, the method comprising the steps of arranging a first object in such a manner that the first object encloses the second object, and applying an electrical signal to the first object, wherein the electrical signal is adapted such that at least a portion of the second object is magnetized. The method works particularly fine when end portions of the second object outside the first object are short-circuited, for instance if two such end portions are connected with each other electrically be a wire guided outside of the first object.

In the following, preferred embodiments of the method for magnetizing an object according to the first independent aspect of the invention will be described. However, these embodiments also apply for the apparatus for magnetizing an object, for the method and the apparatus for calibrating a force and torque sensor device, for the use of an apparatus for magnetizing an object in particular technical fields, and for the use of an apparatus for calibrating a force and torque sensor device in particular technical fields, according to other independent aspects of the invention.

The first electrical signal may be a first pulse signal or a sequence of subsequent pulse signals. Such a pulse signal can particularly be a signal which is different from zero only for a defined interval of time.

Preferably, in a time versus current diagram, the first pulse signal has a fast raising edge which is essentially vertical and has a slow falling edge. With such a pulse signal, the magnetically encoded region obtained has a high quality. It is also possible that a plurality of such pulses are subsequently applied to form a magnetically encoded region.

A second electrical signal may be applied to the second object after having applied the first electrical signal, wherein the second electrical signal may be adapted such that at least a portion of the first object and/or of the second object is magnetized, and wherein the second electrical signal differs from the first electrical signal concerning at least one of the group consisting of amplitude, sign, signal shape and duration.

According to this embodiment, two pulses with opposite flowing direction of the electrical current may be applied to the second object.

The second electrical signal may be a second pulse signal or a sequence of subsequent pulse signals, which, in a time versus current diagram may have a fast raising edge which is essentially vertical and may have a slow falling edge.

According to an embodiment of the method of the invention, the first object may be magnetized by applying the first electrical signal and the second electrical signal such that in a direction essentially perpendicular to a surface of the first object and/or of the second object, a magnetic field structure is generated such that there is a first magnetic flow in a first direction and a second magnetic flow in a second direction, wherein the first direction is opposite to the second direction. This geometrical orientation of the two layers of

magnetization results from two different pulses applied to the magnetizable material, so that a PCME-like sensor according to the below described technology may be manufactured.

The second electrical signal may also be an electrical current or an electrical voltage.

In the following, preferred embodiments of the apparatus for magnetizing an object according to the second independent aspect of the invention will be described. However, these embodiments also apply for the method for magnetizing an object, for the method and the apparatus for calibrating a force and torque sensor device, for the use of an apparatus for magnetizing an object in particular technical fields, and for the use of an apparatus for calibrating a force and torque sensor device in particular technical fields, according to other independent aspects of the invention.

The first object may be a hollow tube. For instance, the first object enclosing the second object may be a hollow cylinder or the like. This structure provides a very symmetric geometry and is easy to manufacture. However, the first object being arranged as a hollow tube does not necessarily have to have a circular cross-section, but may also have a cross-section with the geometry of a polygon (e.g. a triangle or a square). Such a more asymmetric configuration may be used to refine sensing properties.

The second object may be a wire or a shaft or a hollow tube. Such a shaft or wire may be arranged along a symmetry axis of the first object, particularly of the first object embodied as a hollow tube. In an embodiment in which the second object is a hollow tube, the radius of the hollow tube as the second object is smaller than the radius of the hollow tube as the first object so that the second object can be surrounded by the first object. The second object being arranged as a hollow tube does not necessarily have to have a circular cross-section, but may also have a cross-section with the geometry of a polygon (e.g. a triangle or a square). Such a more asymmetric configuration may be used to refine sensing properties.

The second object may be arranged at a centre of the first object. In this configuration, a very symmetric current and magnetic field distribution is achieved.

The electrical signal source may comprise a capacitor bank. Such a capacitor bank comprises a plurality of capacitors which together may generate a pulse signal with a very high current amplitude and a small time duration, particularly for magnetizing large objects, as they may occur in the field of mining and drilling equipment. Such a capacitor bank may, for instance, have a capacity of 0.5 F. As an alternative to a capacitor bank, the electrical signal source/ electrical power source may comprise a conventional power supply unit or power pack.

The first object may have a first connection and may have a second connection, and the second object may have a first electrical connection and a second electrical connection. The second electrical connection of the first object may be coupled to the first electrical connection of the second object. According to this embodiment, the two objects are coupled in a manner that a portion, preferably an end portion, of the first object is coupled to a portion, preferably an end portion, of the second object. By this configuration, the current flowing through the second object is injected into the first object, so that a "feedback" of the magnetic field generating current is achieved. By this feedback, a counter magnetic field is generated in the first object which, together with the current flowing through the second object, provides a very symmetric configuration and yields an advantageous current distribution within the object. A torque and force sensor with a magnetic encoding of this kind, has a very high signal to noise ratio and only a small hysteresis behaviour.

Referring to the previously described embodiment, the electrical signal source may be connected such that a first electrical signal is applyable between the first electrical connection of the first object and the second electrical connection of the second object. According to this circuitry, the current is flowing from the first electrical connection of the first object to the

second electrical connection of the first object, from there to the first electrical connection of the second object, and from there to the second electrical connection of the second object.

The first object may have a third electrical connection, and the second object may have a third electrical connection.

Referring to this embodiment, the electrical signal source may be connected such that a first electrical signal is applyable between the first electrical connection of the first object and the second electrical connection of the second object, and such that a second electrical signal is applyable between the third electrical connection of the first object and the third electrical connection of the second object. This configuration allows to apply magnetizing currents from both end portions of the first and second objects, whereas the first and second objects are coupled electrically at their centre portions with each other.

The apparatus may further comprise an electrically conductive coupling element arranged to couple the second electrical connection of the first object to the first electrical connection of the second object. Such a coupling element may be an electrically conductive plate, like a metal plate, which may be coupled with an end portion of a shaft as the second object and coupled with an end surface of a hollow tube as the first object. However, the electrically conductive coupling element may also be realized as a simple wire or the like. The electrically conductive coupling element may also be realized as an electrically conducting liquid, e.g. on the basis of mercury.

The second object, in addition to the first object, may be adapted to be magnetized when the first electrical signal is applied. In other words, according to the described arrangement of the first object enclosing the second object, both of the objects can be magnetized and used as magnetized objects of a torque or force sensor.

The second object may comprise a first connection and a second connection, wherein the electrical signal source may be connected between the first connection and the second connection of the second object. According to this circuitry, the electrical signal source may be disconnected from the first object. In other words, this configuration can be considered as a transformator-like arrangement, wherein the first object surrounding the second object can be magnetized without any direct ohmic contact between the two objects. In this context, the magnetization of the first object is generated by the electrical signal propagating through the second object and forcing elementary magnets of the material of the first object to become aligned.

According to a preferred embodiment, a portion of the second object may be free from an enclosure with the first object, and the apparatus may further comprise a shielding element which is arranged and adapted to electromagnetically shield the portion of the second object being free from an enclosure with the first object from the first object. This embodiment takes into account that a wiring of the second object back to the electrical signal source may also produce a magnetic field which influences the first object in a way that the magnetization generated by the part of the second object being enclosed or surrounded by the first object is weakened. In order to avoid such an undesired weakening and to achieve a homogeneous and reproducible magnetization of the first object, the shielding element shields the magnetic field generated by the part of the wiring of the second object which is not covered by the first object.

Such a shielding element may be an element, for instance a tube, which may be optionally made of a magnetizable material which is arranged between the first object and the portion of the second object being from an enclosure with the first object. In this configuration, the shielding element forms some kind of magnetic "shadow" to magnetically decouple the first object from the part of the second object which is not covered by the second object.

Alternatively, the shielding element may be a tube (optionally made of a magnetizable material) which is arranged to enclose the portion of the second object being free from an enclosure with the first object. According to this embodiment, the shielding tube surrounds at least a part of the part of the second object which is not surrounded by the first element.

As a further alternative, the shielding element may comprise a plurality of tubes (optionally made of a magnetizable material) which are arranged surrounding at least a part of the portion of the second object being free from an enclosure with the first object. Such shielding tubes may be arranged symmetrically around the part of the first object to be shielded.

In the following, preferred embodiments of the apparatus for calibrating a force and torque sensor device according to the forth independent aspect of the invention will be described. However, these embodiments also apply for the method and apparatus for magnetizing an object, for the method for calibrating a force and torque sensor device, for the use of an apparatus for magnetizing an object in particular technical fields, and for the use of an apparatus for calibrating a force and torque sensor device in particular technical fields, according to other independent aspects of the invention.

In the calibrating apparatus, the pre-known force generating element may be a pre-known weight. This pre-known weight, for instance 1000 kg, may be simply put on the top of a hollow cylinder-like force and torque sensor device to be calibrated and forms a constant and pre-known axial load applied to the sensor device, so that a highly accurate calibration is possible.

Alternatively, the pre-known force generating element may be adapted to apply a pre-known shear stress. Also by applying a shear stress, a pair of data values (force; resulting magnetic signal) can be obtained as a basis for a calibration.

Alternatively, the pre-known force generating element may be adapted to be a pre-known torque, particularly a pre-known reactive torque.

The above and other aspects, objects, features and advantages of the present invention will become apparent from the following description and the appended claim, taken in conjunction with the accompanying drawings in which like parts or elements are denoted by like reference numbers.

Brief Description of the Drawings

The accompanying drawings, which are included to provide a further understanding of the invention and constitute a part of the specification illustrate embodiments of the invention.

In the drawings:

Fig. 1A shows a magnetizing apparatus without involving an object enclosing another object,

Fig. 1B shows a magnetizing apparatus according to the invention involving an object enclosing another object,

Fig. 1C shows a schematic view of a torque and force sensing device with a magnetically encoded region formed according to the invention,

Fig. 1D shows a signal versus torque diagram of a torque and force sensing device magnetized with the magnetizing apparatus shown in Fig. 1A,

Fig. 1E shows a signal versus torque diagram of a torque and force sensing device magnetized with the magnetizing apparatus shown in Fig. 1B,

Fig. 2 is a schematic view illustrating the principle of a method for magnetizing an object according to the invention,

Figs. 3A and **3B** are schematic views illustrating an apparatus for magnetizing an object according to the invention,

Fig. 3C is a schematic view illustrating another apparatus for magnetizing an object according to the invention,

Fig. 3D is a diagram illustrating a pulse signal for magnetizing a object according to an apparatus as shown in Figs. 3A to 3C,

Figs. 4A, 4B illustrate another embodiment of an apparatus for magnetizing an object according to the invention,

Fig. 5 illustrates still another apparatus for magnetizing an object according to an embodiment of the invention,

Figs. 6A to **6D** show top views of different apparatuses for magnetizing an object according to embodiments of the invention,

Fig. 7 shows another apparatus for magnetizing an object according to the invention,

Figs. 8A, 8B show different views of an apparatus for calibrating a force and torque sensor device according to the invention,

Figs. 9A, 9B show schematic views of force and torque sensor devices according to the invention,

Fig. 10 shows different views of magnetically encoded hollow cylinders,

Fig. 11 shows views of a sensing device according to the invention,

Fig.12 to **Fig.67** illustrate the PCME technology which, according to the invention, is preferably used to magnetize a magnetizable object.

Fig. 68 illustrates still another apparatus for magnetizing an object,

Fig. 69 illustrates still another apparatus for magnetizing an object according to an embodiment of the invention,

Fig. 70 shows another apparatus for calibrating a force and torque sensor device according to the invention.

Detailed Description of Preferred Embodiments of the Invention

Fig. 1A shows a magnetizing apparatus 140 for magnetizing a shaft 150 to form a magnetically encoded region on the shaft 150. The magnetizing apparatus 140 does not involve a shaft which is enclosed by another object. When a current signal is applied between different ends of the shaft 150, the shaft 150 is magnetized.

Fig. 1B shows a magnetizing apparatus 160 according to the invention involving a hollow tube 121 enclosing a shaft 150 (not shown in Fig. 1B) to be magnetized. An end portion of the shaft 150 is coupled with an end portion of the hollow tube 121 enclosing the shaft 150. When a current signal is applied to the shaft 150, the current is injected in the hollow tube 121. The magnetic field generated by the current flowing in the hollow tube 121 stabilizes the current distribution in the shaft 150. Thus, the shaft 150 is magnetized in a very homogenous manner.

Fig. 1C shows a schematic view of a torque and force sensing device 170 with a magnetically encoded region 122 formed according to the magnetization generation process carried out with the magnetizing apparatus 160. The length of the magnetically encoded region 122 is defined by the length along which the current flows during the magnetization procedure (i.e. depends on the geometry of the contacts for injecting a magnetizing current).

Fig. 1C shows the torque sensor 170 having the shaft 150 which may rotate with a predetermined value of torque, wherein a portion of the shaft 150 is magnetized to form a magnetically encoded region 122. When the shaft 150 rotates, the magnetically encoded region 122 generates a magnetic signal in a magnetic field detecting coil 123.

Fig. 1D shows a signal versus torque diagram 100 (an experimentally measured curve and a schematic curve emphasizing the features of the measured curve) of a torque and force sensing device magnetized with the magnetizing apparatus 140 shown in Fig. 1A.

Fig. 1E shows a signal versus torque diagram 110 (an experimentally measured curve and a schematic curve emphasizing the features of the measured curve) of a torque and force sensing device 170 magnetized with the magnetizing apparatus 160 shown in Fig. 1B.

The diagrams 100, 110 of Fig. 1D and Fig. 1E each have an abscissa 101 along which a torque is shown which is applied to a shaft with a magnetically encoded region. Figs. 1D and

1E show along an ordinate 102 the signal as detected by coil 123 when a particular value of the torque as plotted along the abscissa 101 is applied.

Figs. 1D and 1E show a hysteresis loop 103 and a best fit line 104, for both cases. As can be seen, the slope of the best fit line 104 is larger in Fig. 1E than in Fig. 1D, and the hysteresis properties are suppressed in Fig. 1E even better than in Fig. 1D.

One of the big challenges of the magnetic field encoding process according to the invention is to achieve a uniform electrical current distribution around a "to be encoded" shaft 150, i.e. to have a properly magnetized region 122. Failing to do so will result in a poor rotational signal uniformity performance and in a poor signal linearity.

Fig. 1D shows the sensors torque signal when the shaft 150 has been processed according to Fig. 1A. The sensor characteristics as shown in Fig. 1D shows some non-linearity which has a negative impact on the sensor signal hysteresis performance.

Processing the shaft 150 to form the magnetically encoded region 122 with the method as shown in Figs. 1B, 2, 3, greatly improves the sensors signal linearity and has a positive impact on the sensors signal hysteresis, which will become much smaller (see Fig. 1E).

The magnetically encoded sensor corresponding to Fig. 1A has a slope of the best fit line 104 of 13.8 mV/Nm, and a hysteresis of 3.72%. In contrast to this, the torque sensor magnetized according to Fig. 1B has, as shown in Fig. 1E, a slope of 15.1 mV/Nm and a hysteresis with only 2.59%.

Thus, the signal-to-noise ratio is significantly improved when the magnetically encoded region 122 is generated according to the invention.

A basic principle of the method for magnetizing an object according to the invention, which can also be denoted as a self-adjusting process, is to generate a counter magnetic field during the actual magnetization process, whereby this counter magnetic field ensures that the electrical signal passes through the shaft 150 very uniformly through the "to be encoded" sensing region 122.

By passing back the electrical signal for magnetizing a part of the shaft 150 to form the magnetically encoded region 122 through the conductive tube 121 enclosing the shaft 150, the magnetic field that develops at the inner side of the tube 121 can work hand in hand with the magnetic field that is developing at the outside of the shaft 150. The shaft 150 is placed at the centre, inside the tube 121, and is not allowed to contact the tube 121, except at desired locations.

Fig. 2 shows a scheme which may be useful for a further understanding of the invention. Thus, the arrangement shown in Fig. 2 shows the solid shaft 150 and the hollow tube 121. An electrical current I is injected in the solid shaft 150 to form a magnetic field around the solid shaft 150, as shown in Fig. 2. When this current I flows through the hollow tube 121, a further magnetic field is also generated in the material of the hollow tube 121. Thus, Fig. 2 is a schematic view illustrating a principle of a method for magnetizing an object according to the invention.

Figs. 3A and **3B** are schematic views illustrating an apparatus for magnetizing an object according to the invention.

In order to magnetize the shaft 150, the hollow tube 121 is arranged to enclose the solid shaft 150. Further, an electrical signal I is applied to the solid shaft 150. As shown in a diagram 310 of Fig. 3D having a time abscissa 301 and having a current ordinate 302, the pulsed current signal 300 has a fast raising edge which is essentially vertical and has a slow falling edge.

As can be further seen in Fig. 3A, the solid shaft 150 is arranged at the centre of the hollow tube 121. The hollow tube 121 has first electrical connection 201 and has a second electrical connection 202, wherein the second electrical connection 202 of the hollow tube 121 is coupled to a first electrical connection 203 of the solid shaft 150. Further, the solid shaft has a second electrical connection 204. An electrical signal source (not shown) is connected such that the current signal I can be applied between the first connection 201 of the hollow tube 121 and the second connection 204 of the solid shaft 150.

Fig. 3B shows another view of the configuration of Fig. 3A.

Because the magnetic flux direction at the inside of the hollow tube 121 (caused by the return electrical current flow direction) is the same rotational direction as the magnetic field that goes around the solid shaft 150 (because of the forward electrical current flow direction), the magnetic field density will distribute itself uniformly in the space between the tube 121 and the shaft 150. Consequently, the electrical current that flows in the solid shaft 150 and the tube 121 will be evenly distributed in both items.

The resulting solution is that the rotational signal uniformity performance of the sensor signal improves greatly (see Fig. 1E), and with this the signal non-linearity and signal hysteresis (will become smaller), and in addition the signal slope increases (more signal at an applied torque).

Particular at the electrical connections between the electrical supply cables and the "to be encoded" shaft 150 the results are very challenging. Even the slightest differences in impedance where the cable connects with the shaft (or tube surface) will cause that the electrical current will be not uniformly distributed around the shaft 150 at this particular area.

As the current is flowing further in the shaft 150, the electrical current density will become more and more uniformly around the shaft 150. If it would be possible to ensure that the electrical current enters uniformly around the shaft 150 right where the electrical wires are connected, then the useful sensing area will become larger (moves nearer to the point where the wires connect with the shaft 150).

The method of magnetizing the shaft according to the invention is exactly doing that: it forces the electrical current to flow most uniformly (in respect when monitoring the current flow density 360° around the shaft).

Thus, the invention has the benefits that it simplifies the way the electrical connections need to be made to the shaft 150. Further, the invention improves greatly several sensor performances. Moreover, the encoding equipment is simplified, and with this the manufacturing equipment costs are reduced.

Fig. 3C shows an alternative arrangement of an apparatus for magnetizing the shaft 150. In addition to the first and the second connections 201, 202, the hollow tube 121 further has a third electrical connection 351, and the solid shaft 150 has a third electrical connection 352. In the case of Fig. 3C, two different pulses I1 and I2 are applied to the array in the manner as shown in Fig. 3C. The first electrical signal I1 is applied between the first electrical connection 201 of the hollow tube 121 and the second electrical connection 204 of the solid shaft 150. A second electrical signal I2 is applied between the third electrical connection 351 of the hollow tube 121 and the third electrical connection 352 of the solid shaft 150.

Further, an electrically conductive coupling element 350 is provided to couple the second electrical connection 202 of the hollow tube 121 to the first electrical connection 203 of the solid shaft 150. The current distribution shown in Fig. 3C achieves a magnetic field distribution which yields a homogeneous current profile in elements 121, 150, thus achieving

a sensor with a well-defined magnetization, i.e. a well-defined magnetically encoded region 122.

Figs. 4A, 4B illustrate another embodiment of an apparatus for magnetizing a shaft 150 according to the invention,

Fig. 4A shows a configuration in which the coupling between the connection 202 of the hollow tube 121 and the connection 203 of the conductive solid shaft 150 are realized by a conductive based plate 400 as a coupling element.

Fig. 4B shows the apparatus of Fig. 4A in a state in which a current is applied. The current flows through the shaft 150, through the plate 400 and from there – in opposite direction compared to the flowing direction in the shaft 150 – through the tube 121. As can be seen in Fig. 4B, the current is applied to the tube 121 via a plurality of electrical connection cables which are arranged circumferentially along the perimeter of the upper circular surface of the tube 121. Such an arrangement with - for instance six or eight - cables yields a very homogeneous current distribution.

As an alternative to the provision of a conductive plate 400 for coupling the tube 121 to the shaft 150, the tube 121 can remain uncoupled from the shaft 150 (i.e. the plate 400 can be omitted), and two oppositely oriented current signals can be flown through the shaft 150 and through the tube 121, wherein the current in the shaft 150 may serve to magnetize the shaft 150, and the current in the tube 121 may serve to provide a counter magnetic field to increase the homogeneity of magnetizing the shaft 150. Thus, two signals are applied simultaneously, one to the tube 121 and the other one to the shaft 150.

In the following, referring to **Fig. 5**, an apparatus 500 for magnetizing a magnetizable tube 501 according to another embodiment of the invention will be described.

The apparatus 500 comprises the magnetizable tube 501, namely a hollow cylinder, a wire 502 having a first part 502a, a second part 502b and a third part 502c, wherein a current can flow through the wire 502. An electrical power source 503 is provided which can inject an electrical current in the wire 502 in an operation state in which a switch 504 is closed. Thus, by closing the switch 504, a pulse current 505 can be injected in wire 502. However, alternatively to the pulse current 505, a pulse as shown in Fig. 3D, for instance, can also be injected in the wire 502. Although a pulse as the one shown in Fig. 3D is preferred, any other appropriate pulse shape like the one shown in Fig. 5 can be injected in the wire 502.

The magnetizable tube 501 is made of industrial steel and has a wall thickness of 4 cm, a diameter of 88 cm and a length of several metres. The tube 501 to be magnetized is arranged in such a manner that the tube 501 encloses the first part 502a of the wire 502. The electrical power source 503 is adapted to apply a pulsed current 505 to the wire 502, wherein the pulsed current 505 is adapted such that the magnetizable tube 501 becomes magnetized. When such a current pulse 505 is applied to the first part 502a of the wire 502, a magnetic field is generated in the vicinity and around the first part 502a of the wire 502 which influences, similar like in the case of a transformator, the elementary magnets within the magnetizable tube 501. Consequently, the pulse 505 will cause the tube 501 to become magnetized.

As can be seen in Fig. 5, the first part 502a of the wire 502 is arranged at the centre of the hollow tube 501. In contrast to the configuration shown in Fig. 3A to 3D, the electrical power source 503 is connected to the wire 502, but is disconnected from the magnetizable tube 501. Further, a hollow shielding cylinder 506 is provided which is manufactured similarly to the magnetizable tube 501. As can be further seen, particularly the third part 502c of the wire 502 is free from an enclosure with the magnetizable tube 501, i.e. is not surrounded by the magnetizable tube 501. The shielding cylinder 506 is arranged and adapted to electromagnetically shield (i.e. decouple) the third part 502c of the wire 502 being free from

an enclosure with the magnetizable tube 501 from the magnetizable tube 501. The shielding tube 506 made of magnetizable material is arranged between the magnetizable tube 501 and the third part 502c of the wire 502. Thus, the current pulse 505 flowing through all parts 502a, 502b, 502c of the wire 502 acts on the magnetizable tube 501 essentially only at the first part 502a which is enclosed by the magnetizable tube 501, whereas the current flowing in a counter direction compared to the first part 502a through the third part 502c is avoided to negatively influence, particularly to weaken, the magnetization generated in the magnetizable tube 501.

Also the second part 502b of the wire 502 can be shielded from the magnetizable tube 501 by a similar shielding element like the shielding cylinder 506.

Fig. 6A shows a schematic top view of the apparatus 500. As can be seen, the shielding cylinder 506 efficiently shields the third part 502c of the wire 502 from the tube 501.

Figs. 6B to **6D** show further embodiments of shielding elements.

Fig. 6B shows a configuration in which four shielding cylinders 600 to 603 are arranged around the third part 502c of the wire 502. Thus, the shielding cylinders 600 to 603 made of magnetizable material are arranged surrounding the portion 502c of the wire 502 which is free from an enclosure with the magnetizable tube 501.

Fig. 6C shows a plurality of cylindrical shafts 610 to 617 which are arranged around the third part 502c of the wire 502 to shield the third part 502 being free of an enclosure with the magnetizable tube 501 from the magnetizable tube 501.

Fig. 6D shows a six tubes 620 to 625 which are arranged to surround the third part 502c.

In the following, referring to **Fig. 7**, an apparatus 700 for magnetizing a magnetizable tube 501 according to another embodiment of the invention will be described.

According to the embodiment of Fig. 7, the shielding cylinder 506 is arranged to surround the third part 502c of the wire 502. Further, the electrical signal source 503 is realized as a bank of (charged) capacitors 701 which may be discharged by closing the switch 504 to generate a pulse as the one shown in Fig. 3D. The magnetizing apparatus 700 is "mobile" which is illustrated by means of a vehicle 702 which transports the capacitor banks 701 to a place at which a magnetizable tube 501 (i.e. drilling equipment at a mining place) shall be magnetized.

Thus, the mobile processing unit of Fig. 7 can be brought closest to drilling or large tooling shafts.

In the following, referring to **Fig. 8A** and **Fig. 8B**, an apparatus 800 for calibrating a force and torque sensor device 810 will be described.

The apparatus 800 comprises the force and torque sensor device 810, a pre-known mass 811 with a weight of 1000 kg and a calibrating unit 818.

The force and torque sensor device 810 has a magnetically encoded region 812 on a hollow tube 813 and four magnetic field detecting coils 814 to 817.

The pre-known weight 811 is put on the top of the force and torque sensor device 810 to apply a pre-known axial force to the magnetized hollow tube 813. The calibrating unit 818 which is connected to the magnetic field detecting coils 814 to 817 is adapted to calibrate the force and torque sensor 810 based on a correlation between the pre-known mass 811 and a detecting signal resulting from the pre-known force of the mass 811.

Thus, a pre-known mass 811 is applied on the top of the horizontally arranged hollow tube 813 which stands on a horizontal and stable base 819. As a consequence of the mass 811 applied to the top of the force and torque sensor device 810 (which may be magnetized in a manner as shown in Fig. 7), the magnetic field generated by the magnetically encoded region 812 changes so that a signal in the magnetic field detecting coils 814 to 817 occurs. Thus, this signal which is processed in the calibration unit 818 is correlated to the pre-known axial force applied to the magnetized tube 813 by the known mass 811. This pair of data pairs, namely the known axial force and the detected signal, can be stored in the calibration unit 818.

The upper surface of the hollow tube 813 (onto which the mass 811 is put) is preferably arranged horizontally so that the vector of the force generated by the mass 811 on the top of the tube 813 is oriented essentially perpendicular to the surface of the hollow tube 813 (or is directed towards the center of the earth). In case that the upper surface of the tube 813 and/or the base 819 is/are not oriented in a horizontal manner, an angular correction calculation may be necessary or desirable.

When the drilling shaft 813 is brought back in the ground and is used for drilling, axial forces and torque applied to the drilling shaft 813 can be measured by the magnetic field detecting coils 814 to 817 and may be compared to the calibration signal. Thus, an absolute measurement of torque and force can be carried out based on a calibration with an axial load 811.

For the calibration, the coils 814 to 817 have to be arranged such that an axial force can be measured. For the torque sensing operation, the coils 814 to 817 have to be arranged such that torque can be measured. Thus, the axes of the coils 814 to 817 may have to be re-oriented, accordingly, when switching from a calibration mode to a measuring mode.

Figs. 9A and **9B** show two possible configurations for arranging the magnetic field detecting coils 814 to 817.

Fig. 10 shows three possible configurations of drilling shafts 1000 having magnetically encoded regions 1001, 1002 or 1003.

The markings 1001 to 1003 symbolize where the drilling shaft 1000 (or rotational power transmitting shaft 1000) have magnetically encoded regions. In real life, the encoding 1001 to 1003 is optically invisible and does not change or interfere with any of the mechanical properties of the shaft 1000. The drilling shaft 1000 can be encoded at a specific location 1001, or at a section 1002, or in its entirety 1003. In many cases, the encoding at a specific location 1001 is advisable for a static system operation only. The encoding options 1002, 1003 are particularly dedicated for applications where the drilling shaft 1000 is rotating or in motion in some ways.

Fig. 11 shows two configurations how magnetic field detecting coils 1100 to 1103 may be arranged around the drilling shaft 1000.

In the following, the so-called PCME ("Pulse-Current-Modulated Encoding") Sensing Technology will be described in detail, which can, according to a preferred embodiment of the invention, be implemented to magnetize a magnetizable object which is then partially demagnetized according to the invention. In the following, the PCME technology will partly described in the context of torque sensing. However, this concept may implemented in the context of position sensing as well.

In this description, there are a number of acronyms used as otherwise some explanations and descriptions may be difficult to read. While the acronyms "ASIC", "IC", and "PCB" are already market standard definitions, there are many terms that are particularly related to the

magnetostriction based NCT sensing technology. It should be noted that in this description, when there is a reference to NCT technology or to PCME, it is referred to exemplary embodiments of the present invention.

Table 1 shows a list of abbreviations used in the following description of the PCME technology.

Acronym	Description	Category
ASIC	Application Specific IC	Electronics
DF	Dual Field	Primary Sensor
EMF	Earth Magnetic Field	Test Criteria
FS	Full Scale	Test Criteria
Hot-Spotting	Sensitivity to nearby Ferro magnetic material	Specification
IC	Integrated Circuit	Electronics
MFS	Magnetic Field Sensor	Sensor Component
NCT	Non Contact Torque	Technology
PCB	Printed Circuit Board	Electronics
PCME	Pulse Current Modulated Encoding	Technology
POC	Proof-of-Concept	
RSU	Rotational Signal Uniformity	Specification
SCSP	Signal Conditioning & Signal Processing	Electronics
SF	Single Field	Primary Sensor
SH	Sensor Host	Primary Sensor
SPHC	Shaft Processing Holding Clamp	Processing Tool
SSU	Secondary Sensor Unit	Sensor Component

Table 1: List of abbreviations

The magnetic principle based mechanical-stress sensing technology allows to design and to produce a wide range of "physical-parameter-sensors" (like Force Sensing, Torque Sensing, and Material Diagnostic Analysis) that can be applied where Ferro-Magnetic materials are used. The most common technologies used to build "magnetic-principle-based" sensors are: Inductive differential displacement measurement (requires torsion shaft), measuring the changes of the materials permeability, and measuring the magnetostriction effects.

Over the last 20 years a number of different companies have developed their own and very specific solution in how to design and how to produce a magnetic principle based torque sensor (i.e. ABB, FAST, Frauenhofer Institute, FT, Kubota, MDI, NCTE, RM, Siemens, and others). These technologies are at various development stages and differ in "how-it-works", the achievable performance, the systems reliability, and the manufacturing / system cost.

Some of these technologies require that mechanical changes are made to the shaft where torque should be measured (chevrons), or rely on the mechanical torsion effect (require a long shaft that twists under torque), or that something will be attached to the shaft itself (press-fitting a ring of certain properties to the shaft surface,), or coating of the shaft surface with a special substance. No-one has yet mastered a high-volume manufacturing process that can be applied to (almost) any shaft size, achieving tight performance tolerances, and is not based on already existing technology patents.

In the following, a magnetostriction principle based Non-Contact-Torque (NCT) Sensing Technology is described that offers to the user a whole host of new features and improved performances, previously not available. This technology enables the realization of a fully-integrated (small in space), real-time (high signal bandwidth) torque measurement, which is reliable and can be produced at an affordable cost, at any desired quantities. This technology

is called: PCME (for Pulse-Current-Modulated Encoding) or Magnetostriction Transversal Torque Sensor.

The PCME technology can be applied to the shaft without making any mechanical changes to the shaft, or without attaching anything to the shaft. Most important, the PCME technology can be applied to any shaft diameter (most other technologies have here a limitation) and does not need to rotate / spin the shaft during the encoding process (very simple and low-cost manufacturing process) which makes this technology very applicable for high-volume application.

In the following, a Magnetic Field Structure (Sensor Principle) will be described.

The sensor life-time depends on a "closed-loop" magnetic field design. The PCME technology is based on two magnetic field structures, stored above each other, and running in opposite directions. When no torque stress or motion stress is applied to the shaft (also called Sensor Host, or SH) then the SH will act magnetically neutral (no magnetic field can be sensed at the outside of the SH).

Fig.12 shows that two magnetic fields are stored in the shaft and running in endless circles. The outer field runs in one direction, while the inner field runs in the opposite direction.

Fig.13 illustrates that the PCME sensing technology uses two Counter-Circular magnetic field loops that are stored on top of each other (Picky-Back mode).

When mechanical stress (like reciprocation motion or torque) is applied at both ends of the PCME magnetized SH (Sensor Host, or Shaft) then the magnetic flux lines of both magnetic structures (or loops) will tilt in proportion to the applied torque.

As illustrated in **Fig.14**, when no mechanical stresses are applied to the SH the magnetic flux lines are running in its original path. When mechanical stresses are applied the magnetic flux lines tilt in proportion to the applied stress (like linear motion or torque).

Depending on the applied torque direction (clockwise or anti-clockwise, in relation to the SH) the magnetic flux lines will either tilt to the right or tilt to the left. Where the magnetic flux lines reach the boundary of the magnetically encoded region, the magnetic flux lines from the upper layer will join-up with the magnetic flux lines from the lower layer and visa-versa. This will then form a perfectly controlled toroidal shape.

The benefits of such a magnetic structure are:

- ☐ Reduced (almost eliminated) parasitic magnetic field structures when mechanical stress is applied to the SH (this will result in better RSU performances).
- ☐ Higher Sensor-Output Signal-Slope as there are two "active" layers that compliment each other when generating a mechanical stress related signal. Explanation: When using a single-layer sensor design, the "tilted" magnetic flux lines that exit at the encoding region boundary have to create a "return passage" from one boundary side to the other. This effort effects how much signal is available to be sensed and measured outside of the SH with the secondary sensor unit.
- ☐ There are almost no limitations on the SH (shaft) dimensions where the PCME technology will be applied to. The dual layered magnetic field structure can be adapted to any solid or hollow shaft dimensions.
- ☐ The physical dimensions and sensor performances are in a very wide range programmable and therefore can be tailored to the targeted application.
- ☐ This sensor design allows to measure mechanical stresses coming from all three dimensions axis, including in-line forces applied to the shaft (applicable as a load-cell). Explanation: Earlier magnetostriction sensor designs (for example from FAST

Technology) have been limited to be sensitive in 2 dimensional axis only, and could not measure in-line forces.

Referring to **Fig.15**, when torque is applied to the SH, the magnetic flux lines from both Counter-Circular magnetic loops are connecting to each other at the sensor region boundaries.

When mechanical torque stress is applied to the SH then the magnetic field will no longer run around in circles but tilt slightly in proportion to the applied torque stress. This will cause the magnetic field lines from one layer to connect to the magnetic field lines in the other layer, and with this form a toroidal shape.

Referring to **Fig.16**, an exaggerated presentation is shown of how the magnetic flux line will form an angled toroidal structure when high levels of torque are applied to the SH.

In the following, features and benefits of the PCM-Encoding (PCME) Process will be described.

The magnetostriction NCT sensing technology from NCTE according to the present invention offers high performance sensing features like:

- ☐ No mechanical changes required on the Sensor Host (already existing shafts can be used as they are)
- ☐ Nothing has to be attached to the Sensor Host (therefore nothing can fall off or change over the shaft-lifetime = high MTBF)
- ☐ During measurement the SH can rotate, reciprocate or move at any desired speed (no limitations on rpm)
- ☐ Very good RSU (Rotational Signal Uniformity) performances
- ☐ Excellent measurement linearity (up to 0.01% of FS)

- High measurement repeatability
- Very high signal resolution (better than 14 bit)
- Very high signal bandwidth (better than 10 kHz)

Depending on the chosen type of magnetostriction sensing technology, and the chosen physical sensor design, the mechanical power transmitting shaft (also called "Sensor Host" or in short "SH") can be used "as is" without making any mechanical changes to it or without attaching anything to the shaft. This is then called a "true" Non-Contact-Torque measurement principle allowing the shaft to rotate freely at any desired speed in both directions.

The here described PCM-Encoding (PCME) manufacturing process according to an exemplary embodiment of the present invention provides additional features no other magnetostriction technology can offer (Uniqueness of this technology):

- More then three times signal strength in comparison to alternative magnetostriction encoding processes (like the "RS" process from FAST).
- Easy and simple shaft loading process (high manufacturing through-putt).
- No moving components during magnetic encoding process (low complexity manufacturing equipment = high MTBF, and lower cost).
- Process allows NCT sensor to be "fine-tuning" to achieve target accuracy of a fraction of one percent.
- Manufacturing process allows shaft "pre-processing" and "post-processing" in the same process cycle (high manufacturing through-putt).
- Sensing technology and manufacturing process is ratio-metric and therefore is applicable to all shaft or tube diameters.
- The PCM-Encoding process can be applied while the SH is already assembled (depending on accessibility) (maintenance friendly).

- ☐ Final sensor is insensitive to axial shaft movements (the actual allowable axial shaft movement depends on the physical "length" of the magnetically encoded region).
- ☐ Magnetically encoded SH remains neutral and has little to non magnetic field when no forces (like torque) are applied to the SH.
- ☐ Sensitive to mechanical forces in all three dimensional axis.

In the following, the Magnetic Flux Distribution in the SH will be described.

The PCME processing technology is based on using electrical currents, passing through the SH (Sensor Host or Shaft) to achieve the desired, permanent magnetic encoding of the Ferro-magnetic material. To achieve the desired sensor performance and features a very specific and well controlled electrical current is required. Early experiments that used DC currents failed because of luck of understanding how small amounts and large amounts of DC electrical current are travelling through a conductor (in this case the "conductor" is the mechanical power transmitting shaft, also called Sensor Host or in short "SH").

Referring to **Fig.17**, an assumed electrical current density in a conductor is illustrated.

It is widely assumed that the electrical current density in a conductor is evenly distributed over the entire cross-section of the conductor when an electrical current (DC) passes through the conductor.

Referring to **Fig.18**, a small electrical current forming magnetic field that ties current path in a conductor is shown.

It is our experience that when a small amount of electrical current (DC) is passing through the conductor that the current density is highest at the centre of the conductor. The two main reasons for this are: The electrical current passing through a conductor generates a magnetic

field that is tying together the current path in the centre of the conductor, and the impedance is the lowest in the centre of the conductor.

Referring to **Fig.19**, a typical flow of small electrical currents in a conductor is illustrated.

In reality, however, the electrical current may not flow in a "straight" line from one connection pole to the other (similar to the shape of electrical lightening in the sky).

At a certain level of electrical current the generated magnetic field is large enough to cause a permanent magnetization of the Ferro-magnetic shaft material. As the electrical current is flowing near or at the centre of the SH, the permanently stored magnetic field will reside at the same location: near or at the centre of the SH. When now applying mechanical torque or linear force for oscillation/reciprocation to the shaft, then shaft internally stored magnetic field will respond by tilting its magnetic flux path in accordance to the applied mechanical force. As the permanently stored magnetic field lies deep below the shaft surface the measurable effects are very small, not uniform and therefore not sufficient to build a reliable NCT sensor system.

Referring to **Fig.20**, a uniform current density in a conductor at saturation level is shown.

Only at the saturation level is the electrical current density (when applying DC) evenly distributed at the entire cross section of the conductor. The amount of electrical current to achieve this saturation level is extremely high and is mainly influenced by the cross section and conductivity (impedance) of the used conductor.

Referring to **Fig.21**, electrical current travelling beneath or at the surface of the conductor (Skin-Effect) is shown.

It is also widely assumed that when passing through alternating current (like a radio frequency signal) through a conductor that the signal is passing through the skin layers of the conductor, called the Skin Effect. The chosen frequency of the alternating current defines the "Location / position" and "depth" of the Skin Effect. At high frequencies the electrical current will travel right at or near the surface of the conductor (A) while at lower frequencies (in the 5 to 10 Hz regions for a 20 mm diameter SH) the electrical alternating current will penetrate more the centre of the shafts cross section (E). Also, the relative current density is higher in the current occupied regions at higher AC frequencies in comparison to the relative current density near the centre of the shaft at very low AC frequencies (as there is more space available for the current to flow through).

Referring to **Fig.22**, the electrical current density of an electrical conductor (cross-section 90 deg to the current flow) when passing through the conductor an alternating current at different frequencies is illustrated.

The desired magnetic field design of the PCME sensor technology are two circular magnetic field structures, stored in two layers on top of each other ("Picky-Back"), and running in opposite direction to each other (Counter-Circular).

Again referring to **Fig.13**, a desired magnetic sensor structure is shown: two endless magnetic loops placed on top of each other, running in opposite directions to each other: Counter-Circular "Picky-Back" Field Design.

To make this magnetic field design highly sensitive to mechanical stresses that will be applied to the SH (shaft), and to generate the largest sensor signal possible, the desired magnetic field structure has to be placed nearest to the shaft surface. Placing the circular magnetic fields to close to the centre of the SH will cause damping of the user available sensor-output-signal slope (most of the sensor signal will travel through the Ferro-magnetic shaft material as it has

a much higher permeability in comparison to air), and increases the non-uniformity of the sensor signal (in relation to shaft rotation and to axial movements of the shaft in relation to the secondary sensor.

Referring to **Fig.23**, magnetic field structures stored near the shaft surface and stored near the centre of the shaft are illustrated.

It may be difficult to achieve the desired permanent magnetic encoding of the SH when using AC (alternating current) as the polarity of the created magnetic field is constantly changing and therefore may act more as a Degaussing system.

The PCME technology requires that a strong electrical current ("uni-polar" or DC, to prevent erasing of the desired magnetic field structure) is travelling right below the shaft surface (to ensure that the sensor signal will be uniform and measurable at the outside of the shaft). In addition a Counter-Circular, "picky back" magnetic field structure needs to be formed.

It is possible to place the two Counter-Circular magnetic field structures in the shaft by storing them into the shaft one after each other. First the inner layer will be stored in the SH, and then the outer layer by using a weaker magnetic force (preventing that the inner layer will be neutralized and deleted by accident. To achieve this, the known "permanent" magnet encoding techniques can be applied as described in patents from FAST technology, or by using a combination of electrical current encoding and the "permanent" magnet encoding.

A much simpler and faster encoding process uses "only" electrical current to achieve the desired Counter-Circular "Picky-Back" magnetic field structure. The most challenging part here is to generate the Counter-Circular magnetic field.

A uniform electrical current will produce a uniform magnetic field, running around the electrical conductor in a 90 deg angle, in relation to the current direction (A). When placing two conductors side-by-side (B) then the magnetic field between the two conductors seems to cancel-out the effect of each other (C). Although still present, there is no detectable (or measurable) magnetic field between the closely placed two conductors. When placing a number of electrical conductors side-by-side (D) the "measurable" magnetic field seems to go around the outside the surface of the "flat" shaped conductor.

Referring to **Fig.24**, the magnetic effects when looking at the cross-section of a conductor with a uniform current flowing through them are shown.

The "flat" or rectangle shaped conductor has now been bent into a "U"-shape. When passing an electrical current through the "U"-shaped conductor then the magnetic field following the outer dimensions of the "U"-shape is cancelling out the measurable effects in the inner halve of the "U".

Referring to **Fig.25**, the zone inside the "U"-shaped conductor seem to be magnetically "Neutral" when an electrical current is flowing through the conductor.

When no mechanical stress is applied to the cross-section of a "U"-shaped conductor it seems that there is no magnetic field present inside of the "U" (F). But when bending or twisting the "U"-shaped conductor the magnetic field will no longer follow its original path (90 deg angle to the current flow). Depending on the applied mechanical forces, the magnetic field begins to change slightly its path. At that time the magnetic-field-vector that is caused by the mechanical stress can be sensed and measured at the surface of the conductor, inside and outside of the "U"-shape. Note: This phenomena is applies only at very specific electrical current levels.

The same applies to the "O"-shaped conductor design. When passing a uniform electrical current through an "O"-shaped conductor (Tube) the measurable magnetic effects inside of the "O" (Tube) have cancelled-out each other (G).

Referring to **Fig.26**, the zone inside the "O"-shaped conductor seem to be magnetically "Neutral" when an electrical current is flowing through the conductor.

However, when mechanical stresses are applied to the "O"-shaped conductor (Tube) it becomes evident that there has been a magnetic field present at the inner side of the "O"-shaped conductor. The inner, counter directional magnetic field (as well as the outer magnetic field) begins to tilt in relation to the applied torque stresses. This tilting field can be clearly sensed and measured.

In the following, an Encoding Pulse Design will be described.

To achieve the desired magnetic field structure (Counter-Circular, Picky-Back, Fields Design) inside the SH, according to an exemplary embodiment of a method of the present invention, unipolar electrical current pulses are passed through the Shaft (or SH). By using "pulses" the desired "Skin-Effect" can be achieved. By using a "unipolar" current direction (not changing the direction of the electrical current) the generated magnetic effect will not be erased accidentally.

The used current pulse shape is most critical to achieve the desired PCME sensor design. Each parameter has to be accurately and repeatable controlled: Current raising time, Constant current on-time, Maximal current amplitude, and Current falling time. In addition it is very critical that the current enters and exits very uniformly around the entire shaft surface.

In the following, a Rectangle Current Pulse Shape will be described.

Referring to **Fig.27**, a rectangle shaped electrical current pulse is illustrated.

A rectangle shaped current pulse has a fast raising positive edge and a fast falling current edge. When passing a rectangle shaped current pulse through the SH, the raising edge is responsible for forming the targeted magnetic structure of the PCME sensor while the flat "on" time and the falling edge of the rectangle shaped current pulse are counter productive.

Referring to **Fig.28**, a relationship between rectangles shaped Current Encoding Pulse-Width (Constant Current On-Time) and Sensor Output Signal Slope is shown.

In the following example a rectangle shaped current pulse has been used to generate and store the Couter-Circilar "Picky-Back" field in a 15 mm diameter, 14CrNi14 shaft. The pulsed electrical current had its maximum at around 270 Ampere. The pulse "on-time" has been electronically controlled. Because of the high frequency component in the rising and falling edge of the encoding pulse, this experiment can not truly represent the effects of a true DC encoding SH. Therefore the Sensor-Output-Signal Slope-curve eventually flattens-out at above 20 mV/Nm when passing the Constant-Current On-Time of 1000 ms.

Without using a fast raising current-pulse edge (like using a controlled ramping slope) the sensor output signal slope would have been very poor (below 10 mV/Nm). Note: In this experiment (using 14CrNi14) the signal hysteresis was around 0.95% of the FS signal (FS = 75 Nm torque).

Referring to **Fig.29**, increasing the Sensor-Output Signal-Slope by using several rectangle shaped current pulses in succession is shown.

The Sensor-Output-Signal slope can be improved when using several rectangle shaped current-encoding-pulses in successions. In comparisons to other encoding-pulse-shapes the fast falling current-pulse signal slope of the rectangle shaped current pulse will prevent that the Sensor-Output-Signal slope may ever reach an optimal performance level. Meaning that after only a few current pulses (2 to 10) have been applied to the SH (or Shaft) the Sensor-Output Signal-Slope will no longer rise.

In the following, a Discharge Current Pulse Shape is described.

The Discharge-Current-Pulse has no Constant-Current ON-Time and has no fast falling edge. Therefore the primary and most felt effect in the magnetic encoding of the SH is the fast raising edge of this current pulse type.

As shown in **Fig.30**, a sharp raising current edge and a typical discharging curve provides best results when creating a PCME sensor.

Referring to **Fig.31**, a PCME Sensor-Output Signal-Slope optimization by identifying the right pulse current is illustrated.

At the very low end of the pulse current scale (0 to 75 A for a 15 mm diameter shaft, 14CrNi14 shaft material) the "Discharge-Current-Pulse type is not powerful enough to cross the magnetic threshold needed to create a lasting magnetic field inside the Ferro magnetic shaft. When increasing the pulse current amplitude the double circular magnetic field structure begins to form below the shaft surface. As the pulse current amplitude increases so does the achievable torque sensor-output signal-amplitude of the secondary sensor system. At around 400A to 425A the optimal PCME sensor design has been achieved (the two counter flowing magnetic regions have reached their most optimal distance to each other and the correct flux density for best sensor performances.

Referring to **Fig.32**, Sensor Host (SH) cross section with the optimal PCME electrical current density and location during the encoding pulse is illustrated.

When increasing further the pulse current amplitude the absolute, torque force related, sensor signal amplitude will further increase (curve 2) for some time while the overall PCME-typical sensor performances will decrease (curve 1). When passing 900A Pulse Current Amplitude (for a 15 mm diameter shaft) the absolute, torque force related, sensor signal amplitude will begin to drop as well (curve 2) while the PCME sensor performances are now very poor (curve 1).

Referring to **Fig.33**, Sensor Host (SH) cross sections and the electrical pulse current density at different and increasing pulse current levels is shown.

As the electrical current occupies a larger cross section in the SH the spacing between the inner circular region and the outer (near the shaft surface) circular region becomes larger.

Referring to **Fig.34**, better PCME sensor performances will be achieved when the spacing between the Counter-Circular "Picky-Back" Field design is narrow (A).

The desired double, counter flow, circular magnetic field structure will be less able to create a close loop structure under torque forces which results in a decreasing secondary sensor signal amplitude.

Referring to **Fig.35**, flattening-out the current-discharge curve will also increase the Sensor-Output Signal-Slope.

When increasing the Current-Pulse discharge time (making the current pulse wider) (B) the Sensor-Output Signal-Slope will increase. However the required amount of current is very high to reduce the slope of the falling edge of the current pulse. It might be more practical to use a combination of a high current amplitude (with the optimal value) and the slowest possible discharge time to achieve the highest possible Sensor-Output Signal Slope.

In the following, Electrical Connection Devices in the frame of Primary Sensor Processing will be described.

The PCME technology (it has to be noted that the term 'PCME' technology is used to refer to exemplary embodiments of the present invention) relies on passing through the shaft very high amounts of pulse-modulated electrical current at the location where the Primary Sensor should be produced. When the surface of the shaft is very clean and highly conductive a multi-point Cupper or Gold connection may be sufficient to achieve the desired sensor signal uniformity. Important is that the Impedance is identical of each connection point to the shaft surface. This can be best achieved when assuring the cable length (L) is identical before it joins the main current connection point (I).

Referring to **Fig.36**, a simple electrical multi-point connection to the shaft surface is illustrated.

However, in most cases a reliable and repeatable multi-point electrical connection can be only achieved by ensuring that the impedance at each connection point is identical and constant. Using a spring pushed, sharpened connector will penetrate possible oxidation or isolation layers (maybe caused by finger prints) at the shaft surface.

Referring to **Fig.37**, a multi channel, electrical connecting fixture, with spring loaded contact points is illustrated.

When processing the shaft it is most important that the electrical current is injected and extracted from the shaft in the most uniform way possible. The above drawing shows several electrical, from each other insulated, connectors that are held by a fixture around the shaft. This device is called a Shaft-Processing-Holding-Clamp (or SPHC). The number of electrical connectors required in a SPHC depends on the shafts outer diameter. The larger the outer diameter, the more connectors are required. The spacing between the electrical conductors has to be identical from one connecting point to the next connecting point. This method is called Symmetrical-"Spot"-Contacts.

Referring to **Fig.38**, it is illustrated that increasing the number of electrical connection points will assist the efforts of entering and exiting the Pulse-Modulated electrical current. It will also increase the complexity of the required electronic control system.

Referring to **Fig.39**, an example of how to open the SPHC for easy shaft loading is shown.

In the following, an encoding scheme in the frame of Primary Sensor Processing will be described.

The encoding of the primary shaft can be done by using permanent magnets applied at a rotating shaft or using electrical currents passing through the desired section of the shaft. When using permanent magnets a very complex, sequential procedure is necessary to put the two layers of closed loop magnetic fields, on top of each other, in the shaft. When using the PCME procedure the electrical current has to enter the shaft and exit the shaft in the most symmetrical way possible to achieve the desired performances.

Referring to **Fig.40**, two SPHCs (Shaft Processing Holding Clamps) are placed at the borders of the planned sensing encoding region. Through one SPHC the pulsed electrical current (I)

will enter the shaft, while at the second SPHC the pulsed electrical current (I) will exit the shaft. The region between the two SPHCs will then turn into the primary sensor.

This particular sensor process will produce a Single Field (SF) encoded region. One benefit of this design (in comparison to those that are described below) is that this design is insensitive to any axial shaft movements in relation to the location of the secondary sensor devices. The disadvantage of this design is that when using axial (or in-line) placed MFS coils the system will be sensitive to magnetic stray fields (like the earth magnetic field).

Referring to **Fig.41**, a Dual Field (DF) encoded region (meaning two independent functioning sensor regions with opposite polarity, side-by-side) allows cancelling the effects of uniform magnetic stray fields when using axial (or in-line) placed MFS coils. However, this primary sensor design also shortens the tolerable range of shaft movement in axial direction (in relation to the location of the MFS coils). There are two ways to produce a Dual Field (DF) encoded region with the PCME technology. The sequential process, where the magnetic encoded sections are produced one after each other, and the parallel process, where both magnetic encoded sections are produced at the same time.

The first process step of the sequential dual field design is to magnetically encode one sensor section (identically to the Single Field procedure), whereby the spacing between the two SPHC has to be halve of the desired final length of the Primary Sensor region. To simplify the explanations of this process we call the SPHC that is placed in the centre of the final Primary Sensor Region the Centre SPHC (C-SPHC), and the SPHC that is located at the left side of the Centre SPHC: L-SPHC.

Referring to **Fig.42**, the second process step of the sequential Dual Field encoding will use the SPHC that is located in the centre of the Primary Sensor region (called C-SPHC) and a second SPHC that is placed at the other side (the right side) of the centre SPHC, called R-SPHC.

Important is that the current flow direction in the centre SPHC (C-SPHC) is identical at both process steps.

Referring to **Fig.43**, the performance of the final Primary Sensor Region depends on how close the two encoded regions can be placed in relation to each other. And this is dependent on the design of the used centre SPHC. The narrower the in-line space contact dimensions are of the C-SPHC, the better are the performances of the Dual Field PCME sensor.

Fig.44 shows the pulse application according to another exemplary embodiment of the present invention. As my be taken from the above drawing, the pulse is applied to three locations of the shaft. Due to the current distribution to both sides of the middle electrode where the current I is entered into the shaft, the current leaving the shaft at the lateral electrodes is only half the current entered at the middle electrode, namely ½ I. The electrodes are depicted as rings which dimensions are adapted to the dimensions of the outer surface of the shaft. However, it has to be noted that other electrodes may be used, such as the electrodes comprising a plurality of pin electrodes described later in this text.

Referring to **Fig.45**, magnetic flux directions of the two sensor sections of a Dual Field PCME sensor design are shown when no torque or linear motion stress is applied to the shaft. The counter flow magnetic flux loops do not interact with each other.

Referring to **Fig.46**, when torque forces or linear stress forces are applied in a particular direction then the magnetic flux loops begin to run with an increasing tilting angle inside the shaft. When the tilted magnetic flux reaches the PCME segment boundary then the flux line interacts with the counterflowing magnetic flux lines, as shown.

Referring to **Fig.47**, when the applied torque direction is changing (for example from clock-wise to counter-clock-wise) so will change the tilting angle of the counterflow magnetic flux structures inside the PCM Encoded shaft.

In the following, a Multi Channel Current Driver for Shaft Processing will be described.

In cases where an absolute identical impedance of the current path to the shaft surface can not be guaranteed, then electrical current controlled driver stages can be used to overcome this problem.

Referring to **Fig.48**, a six-channel synchronized Pulse current driver system for small diameter Sensor Hosts (SH) is shown. As the shaft diameter increases so will the number of current driver channels.

In the following, Bras Ring Contacts and Symmetrical "Spot" Contacts will be described.

When the shaft diameter is relative small and the shaft surface is clean and free from any oxidations at the desired Sensing Region, then a simple "Bras"-ring (or Copper-ring) contact method can be chosen to process the Primary Sensor.

Referring to **Fig.49**, bras-rings (or Copper-rings) tightly fitted to the shaft surface may be used, with solder connections for the electrical wires. The area between the two Bras-rings (Copper-rings) is the encoded region.

However, it is very likely that the achievable RSU performances are much lower then when using the Symmetrical "Spot" Contact method.

In the following, a Hot-Spotting concept will be described.

A standard single field (SF) PCME sensor has very poor Hot-Spotting performances. The external magnetic flux profile of the SF PCME sensor segment (when torque is applied) is very sensitive to possible changes (in relation to Ferro magnetic material) in the nearby environment. As the magnetic boundaries of the SF encoded sensor segment are not well defined (not "Pinned Down") they can "extend" towards the direction where Ferro magnet material is placed near the PCME sensing region.

Referring to **Fig.50**, a PCME process magnetized sensing region is very sensitive to Ferro magnetic materials that may come close to the boundaries of the sensing regions.

To reduce the Hot-Spotting sensor sensitivity the PCME sensor segment boundaries have to be better defined by pinning them down (they can no longer move).

Referring to **Fig.51**, a PCME processed Sensing region with two "Pinning Field Regions" is shown, one on each side of the Sensing Region.

By placing Pinning Regions closely on either side the Sensing Region, the Sensing Region Boundary has been pinned down to a very specific location. When Ferro magnetic material is coming close to the Sensing Region, it may have an effect on the outer boundaries of the Pinning Regions, but it will have very limited effects on the Sensing Region Boundaries.

There are a number of different ways, according to exemplary embodiments of the present invention how the SH (Sensor Host) can be processed to get a Single Field (SF) Sensing Region and two Pinning Regions, one on each side of the Sensing Region. Either each region is processed after each other (Sequential Processing) or two or three regions are processed

simultaneously (Parallel Processing). The Parallel Processing provides a more uniform sensor (reduced parasitic fields) but requires much higher levels of electrical current to get to the targeted sensor signal slope.

Referring to **Fig.52**, a parallel processing example for a Single Field (SF) PCME sensor with Pinning Regions on either side of the main sensing region is illustrated, in order to reduce (or even eliminate) Hot-Spotting.

A Dual Field PCME Sensor is less sensitive to the effects of Hot-Spotting as the sensor centre region is already Pinned-Down. However, the remaining Hot-Spotting sensitivity can be further reduced by placing Pinning Regions on either side of the Dual-Field Sensor Region.

Referring to **Fig.53**, a Dual Field (DF) PCME sensor with Pinning Regions either side is shown.

When Pinning Regions are not allowed or possible (example: limited axial spacing available) then the Sensing Region has to be magnetically shielded from the influences of external Ferro Magnetic Materials.

In the following, the Rotational Signal Uniformity (RSU) will be explained.

The RSU sensor performance are, according to current understanding, mainly depending on how circumferentially uniform the electrical current entered and exited the SH surface, and the physical space between the electrical current entry and exit points. The larger the spacing between the current entry and exit points, the better is the RSU performance.

Referring to **Fig.54**, when the spacings between the individual circumferential placed current entry points are relatively large in relation to the shaft diameter (and equally large are the spacings between the circumferentially placed current exit points) then this will result in very poor RSU performances. In such a case the length of the PCM Encoding Segment has to be as large as possible as otherwise the created magnetic field will be circumferentially non-uniform.

Referring to **Fig.55**, by widening the PCM Encoding Segment the circumferentially magnetic field distribution will become more uniform (and eventually almost perfect) at the halve distance between the current entry and current exit points. Therefore the RSU performance of the PCME sensor is best at the halve way-point between of the current-entry / current-exit points.

Next, the basic design issues of a NCT sensor system will be described.

Without going into the specific details of the PCM-Encoding technology, the end-user of this sensing technology need to now some design details that will allow him to apply and to use this sensing concept in his application. The following pages describe the basic elements of a magnetostriction based NCT sensor (like the primary sensor, secondary sensor, and the SCSP electronics), what the individual components look like, and what choices need to be made when integrating this technology into an already existing product.

In principle the PCME sensing technology can be used to produce a stand-alone sensor product. However, in already existing industrial applications there is little to none space available for a "stand-alone" product. The PCME technology can be applied in an existing product without the need of redesigning the final product.

In case a stand-alone torque sensor device or position detecting sensor device will be applied to a motor-transmission system it may require that the entire system need to undergo a major design change.

In the following, referring to Fig.56, a possible location of a PCME sensor at the shaft of an engine is illustrated.

Next, Sensor Components will be explained.

A non-contact magnetostriction sensor (NCT-Sensor), as shown in **Fig.57**, may consist, according to an exemplary embodiment of the present invention, of three main functional elements: The Primary Sensor, the Secondary Sensor, and the Signal Conditioning & Signal Processing (SCSP) electronics.

Depending on the application type (volume and quality demands, targeted manufacturing cost, manufacturing process flow) the customer can chose to purchase either the individual components to build the sensor system under his own management, or can subcontract the production of the individual modules.

Fig.58 shows a schematic illustration of components of a non-contact torque sensing device. However, these components can also be implemented in a non-contact position sensing device.

In cases where the annual production target is in the thousands of units it may be more efficient to integrate the "primary-sensor magnetic-encoding-process" into the customers manufacturing process. In such a case the customer needs to purchase application specific "magnetic encoding equipment".

In high volume applications, where cost and the integrity of the manufacturing process are critical, it is typical that NCTE supplies only the individual basic components and equipment necessary to build a non-contact sensor:

- ICs (surface mount packaged, Application-Specific Electronic Circuits)
- MFS-Coils (as part of the Secondary Sensor)
- Sensor Host Encoding Equipment (to apply the magnetic encoding on the shaft = Primary Sensor)

Depending on the required volume, the MFS-Coils can be supplied already assembled on a frame, and if desired, electrically attached to a wire harness with connector. Equally the SCSP (Signal Conditioning & Signal Processing) electronics can be supplied fully functional in PCB format, with or without the MFS-Coils embedded in the PCB.

Fig.59 shows components of a sensing device.

As can be seen from **Fig.60**, the number of required MFS-coils is dependent on the expected sensor performance and the mechanical tolerances of the physical sensor design. In a well designed sensor system with perfect Sensor Host (SH or magnetically encoded shaft) and minimal interferences from unwanted magnetic stray fields, only 2 MFS-coils are needed. However, if the SH is moving radial or axial in relation to the secondary sensor position by more than a few tenths of a millimeter, then the number of MFS-coils need to be increased to achieve the desired sensor performance.

In the following, a control and/or evaluation circuitry will be explained.

The SCSP electronics, according to an exemplary embodiment of the present invention, consist of the NCTE specific ICs, a number of external passive and active electronic circuits,

the printed circuit board (PCB), and the SCSP housing or casing. Depending on the environment where the SCSP unit will be used the casing has to be sealed appropriately.

Depending on the application specific requirements NCTE (according to an exemplary embodiment of the present invention) offers a number of different application specific circuits:

- ☐ Basic Circuit
- ☐ Basic Circuit with integrated Voltage Regulator
- ☐ High Signal Bandwidth Circuit
- ☐ Optional High Voltage and Short Circuit Protection Device
- ☐ Optional Fault Detection Circuit

Fig.61 shows a single channel, low cost sensor electronics solution.

Fig.62 shows a dual channel, short circuit protected system design with integrated fault detection. This design consists of 5 ASIC devices and provides a high degree of system safety. The Fault-Detection IC identifies when there is a wire breakage anywhere in the sensor system, a fault with the MFS coils, or a fault in the electronic driver stages of the "Basic IC".

Next, the Secondary Sensor Unit will be explained.

The Secondary Sensor may, according to one embodiment shown in **Fig.63**, consist of the elements: One to eight MFS (Magnetic Field Sensor) Coils, the Alignment- & Connection-Plate, the wire harness with connector, and the Secondary-Sensor-Housing.

The MFS-coils may be mounted onto the Alignment-Plate. Usually the Alignment-Plate allows that the two connection wires of each MFS-Coil are soldered / connected in the appropriate way. The wire harness is connected to the alignment plate. This, completely assembled with the MFS-Coils and wire harness, is then embedded or held by the Secondary-Sensor-Housing.

The main element of the MFS-Coil is the core wire, which has to be made out of an amorphous-like material.

Depending on the environment where the Secondary-Sensor-Unit will be used, the assembled Alignment Plate has to be covered by protective material. This material can not cause mechanical stress or pressure on the MFS-coils when the ambient temperature is changing.

In applications where the operating temperature will not exceed +110 deg C the customer has the option to place the SCSP electronics (ASIC) inside the secondary sensor unit (SSU). While the ASIC devices can operated at temperatures above +125 deg C it will become increasingly more difficult to compensate the temperature related signal-offset and signal-gain changes.

The recommended maximal cable length between the MFS-coils and the SCSP electronics is 2 meters. When using the appropriate connecting cable, distances of up to 10 meters are achievable. To avoid signal-cross-talk in multi-channel applications (two independent SSUs operating at the same Primary Sensor location = Redundant Sensor Function), specially shielded cable between the SSUs and the SCSP Electronics should be considered.

When planning to produce the Secondary-Sensor-Unit (SSU) the producer has to decide which part / parts of the SSU have to be purchased through subcontracting and which manufacturing steps will be made in-house.

In the following, Secondary Sensor Unit Manufacturing Options will be described.

When integrating the NCT-Sensor into a customized tool or standard transmission system then the systems manufacturer has several options to choose from:

- ☐ custom made SSU (including the wire harness and connector)
- ☐ selected modules or components; the final SSU assembly and system test may be done under the customer's management.
- ☐ only the essential components (MFS-coils or MFS-core-wire, Application specific ICs) and will produce the SSU in-house.

Fig.64 illustrates an exemplary embodiment of a Secondary Sensor Unit Assembly.

Next, a Primary Sensor Design is explained.

The SSU (Secondary Sensor Units) can be placed outside the magnetically encoded SH (Sensor Host) or, in case the SH is hollow, inside the SH. The achievable sensor signal amplitude is of equal strength but has a much better signal-to-noise performance when placed inside the hollow shaft.

Fig.65 illustrates two configurations of the geometrical arrangement of Primary Sensor and Secondary Sensor.

Improved sensor performances may be achieved when the magnetic encoding process is applied to a straight and parallel section of the SH (shaft). For a shaft with 15 mm to 25 mm diameter the optimal minimum length of the Magnetically Encoded Region is 25 mm. The sensor performances will further improve if the region can be made as long as 45 mm (adding

Guard Regions). In complex and highly integrated transmission (gearbox) systems it will be difficult to find such space. Under more ideal circumstances, the Magnetically Encoding Region can be as short as 14 mm, but this bears the risk that not all of the desired sensor performances can be achieved.

As illustrated in **Fig.66**, the spacing between the SSU (Secondary Sensor Unit) and the Sensor Host surface, according to an exemplary embodiment of the present invention, should be held as small as possible to achieve the best possible signal quality.

Next, the Primary Sensor Encoding Equipment will be described.

An example is shown in **Fig.67**.

Depending on which magnetostriction sensing technology will be chosen, the Sensor Host (SH) needs to be processed and treated accordingly. The technologies vary by a great deal from each other (ABB, FAST, FT, Kubota, MDI, NCTE, RM, Siemens, ...) and so does the processing equipment required. Some of the available magnetostriction sensing technologies do not need any physical changes to be made on the SH and rely only on magnetic processing (MDI, FAST, NCTE).

While the MDI technology is a two phase process, the FAST technology is a three phase process, and the NCTE technology a one phase process, called PCM Encoding.

One should be aware that after the magnetic processing, the Sensor Host (SH or Shaft), has become a "precision measurement" device and has to be treated accordingly. The magnetic processing should be the very last step before the treated SH is carefully placed in its final location.

The magnetic processing should be an integral part of the customer's production process (in-house magnetic processing) under the following circumstances:

- ☐ High production quantities (like in the thousands)
- ☐ Heavy or difficult to handle SH (e.g. high shipping costs)
- ☐ Very specific quality and inspection demands (e.g. defense applications)

In all other cases it may be more cost effective to get the SH magnetically treated by a qualified and authorized subcontractor, such as NCTE. For the "in-house" magnetic processing dedicated manufacturing equipment is required. Such equipment can be operated fully manually, semi-automated, and fully automated. Depending on the complexity and automation level the equipment can cost anywhere from EUR 20k to above EUR 500k.

In the following, referring to **Fig. 68**, an apparatus 6800 for magnetizing an object will be explained.

As shown in Fig.68, the shaft 150 enclosed by the hollow tube 121 can be magnetized by applying an electrical signal generated by the electrical power source 503 to the hollow tube 121. The apparatus 6800 allows magnetizing the shaft 150 by arranging the hollow tube 121 in such a manner that the hollow tube 121 encloses the shaft 150, and by applying an electrical signal via a plurality of circumferentially arranged contacts to the hollow tube 121. The electrical signal generated by the electrical power source 503 is preferably a pulsed signal such that at least a portion of the shaft 150 is magnetized. As shown in Fig. 68, two end portions of the shaft 150 outside the hollow tube 121 are short-circuited by a wire 6801 located outside the hollow tube 121.

Fig. 69 illustrates still another apparatus 6900 for magnetizing an object according to an embodiment of the invention.

The function of the apparatus 6900 is very similar to the function of the apparatus shown in Fig. 4A, Fig. 4B with the difference that the electrically conductive plate 400 is substituted by an electrically conductive fluid 6902 (e.g. mercury) which serves to electrically contact the shaft 150 to the hollow tube 121.

In the following, it is described how the apparatus 6900 is operated. A (for instance electrically insulating) spacer element 6901 in the form of a hollow cylinder with an inside diameter which essentially equals to the diameter of the shaft 150 and with an outside diameter which essentially equals to the inside diameter of the hollow tube 121 is arranged to seal and space the volume between the hollow tube 121 and the shaft 150 located within the hollow tube. Subsequently, the electrically conductive fluid 6902 is injected in the array 6900 to fill the space delimited by the hollow tube 121 and the shaft 150 and the spacer element 6901 to electrically couple the hollow tube 121 and the shaft 150 in a very flexible manner.

In the following, referring to **Fig. 70**, an apparatus 7000 for calibrating a force and torque sensor device according to the invention will be explained.

The apparatus 7000 comprises a base 7001 for receiving a shaft 7002 of a torque sensing device. The torque sensing device further includes two magnetic field detection coils 7004 and a magnetically encoded region 7003 which may be formed, for instance, by the above-described PCME technology. The base 7001 receives the shaft 7002 in such a manner that the shaft cannot be moved or rotated by an applied force. A motor 7005 is adapted to drive a rotatable element 7006 (e.g. a flywheel) which in term can rotate in a controllable manner and which is coupled to the shaft 7002 such that a mechanical impulse of the rotatable element 7006 can be transferred to the shaft 7002 to apply a (reactive) torque to the shaft 7002. As a response to such a calibrating torque of a known value, a signal can be detected by the coils 7004 which can serve for a calibration of the torque sensing device. Thus, the apparatus 7000

has the driven rotatable element 7006 as a pre-known torque generating element. Particularly, a sudden change of the rotation state of the rotatable element 7006 (e.g. a sudden brake signal) is useful as a source of (reactive) torque applied as a calibrating signal to the torque sensing device.

It should be noted that the term "comprising" does not exclude other elements or steps and the "a" or "an" does not exclude a plurality. Also elements described in association with different embodiments may be combined.

What Is claimed is:

1. A method for magnetizing a first object and/or a second object, the method comprising the steps of

arranging a first object in such a manner that the first object encloses a second object;

applying a first electrical signal to the second object, wherein the first electrical signal is adapted such that at least a portion of the first object and/or of the second object is magnetized;

wherein the first electrical signal is a first pulse signal;

wherein, in a time versus current diagram, the first pulse signal has a fast raising edge which is essentially vertical and has a slow falling edge;

wherein the first electrical signal is a current or a voltage;

wherein a second electrical signal is applied to the second object after having applied the first electrical signal, wherein the second electrical signal is adapted such that at least a portion of the first object and/or of the second object is magnetized, and wherein the second electrical signal differs from the first electrical signal concerning at least one of the group consisting of amplitude, sign, signal shape and duration;

wherein the second electrical signal is a second pulse signal;

wherein, in a time versus current diagram, the second pulse signal has a fast raising edge which is essentially vertical and has a slow falling edge;

wherein the first object and/or the second object is magnetized by applying the first electrical signal and the second electrical signal such that in a direction essentially perpendicular to a surface of the first object and/or of the second object, a magnetic field structure is generated such that there is a first magnetic flow in a first direction and a second magnetic flow in a second direction, wherein the first direction is opposite to the second direction;

wherein the second electrical signal is a current or a voltage.

Abstract

A method and an apparatus for magnetizing an object, a method and an apparatus for calibrating a force and torque sensor device, a use of an apparatus for magnetizing an object in particular fields, and a use of an apparatus for calibrating a force and torque sensor device in particular fields

A method for magnetizing a first object and/or a second object comprises the steps of arranging a first object in such a manner that the first object encloses a second object, and applying a first electrical signal to the second object, wherein the first electrical signal is adapted such that at least a portion of the first object and/or of the second object is magnetized.

(Fig.4B)

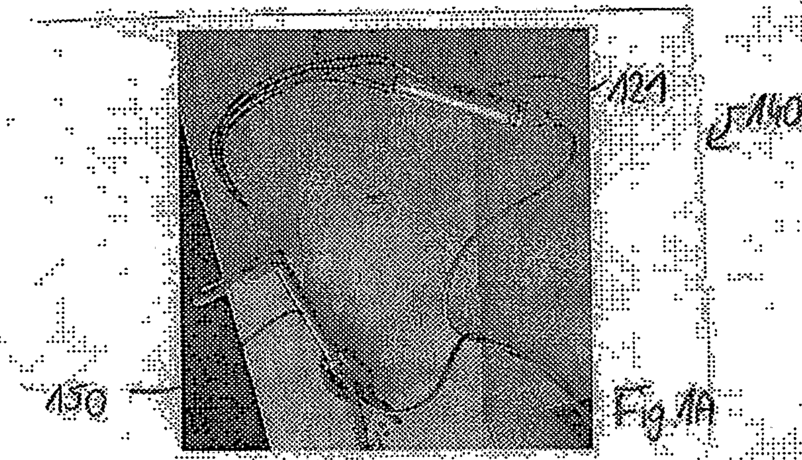


Fig 1A

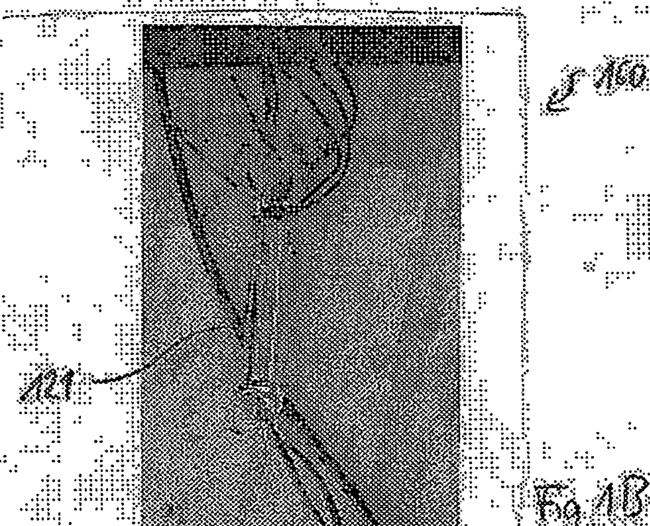


Fig 1B

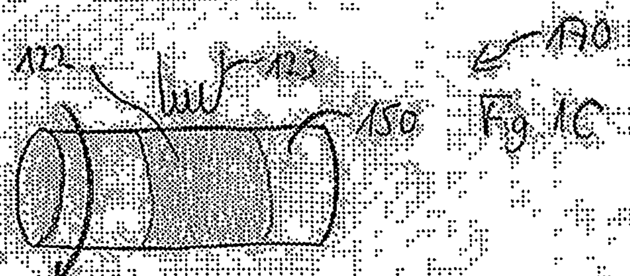


Fig 1C

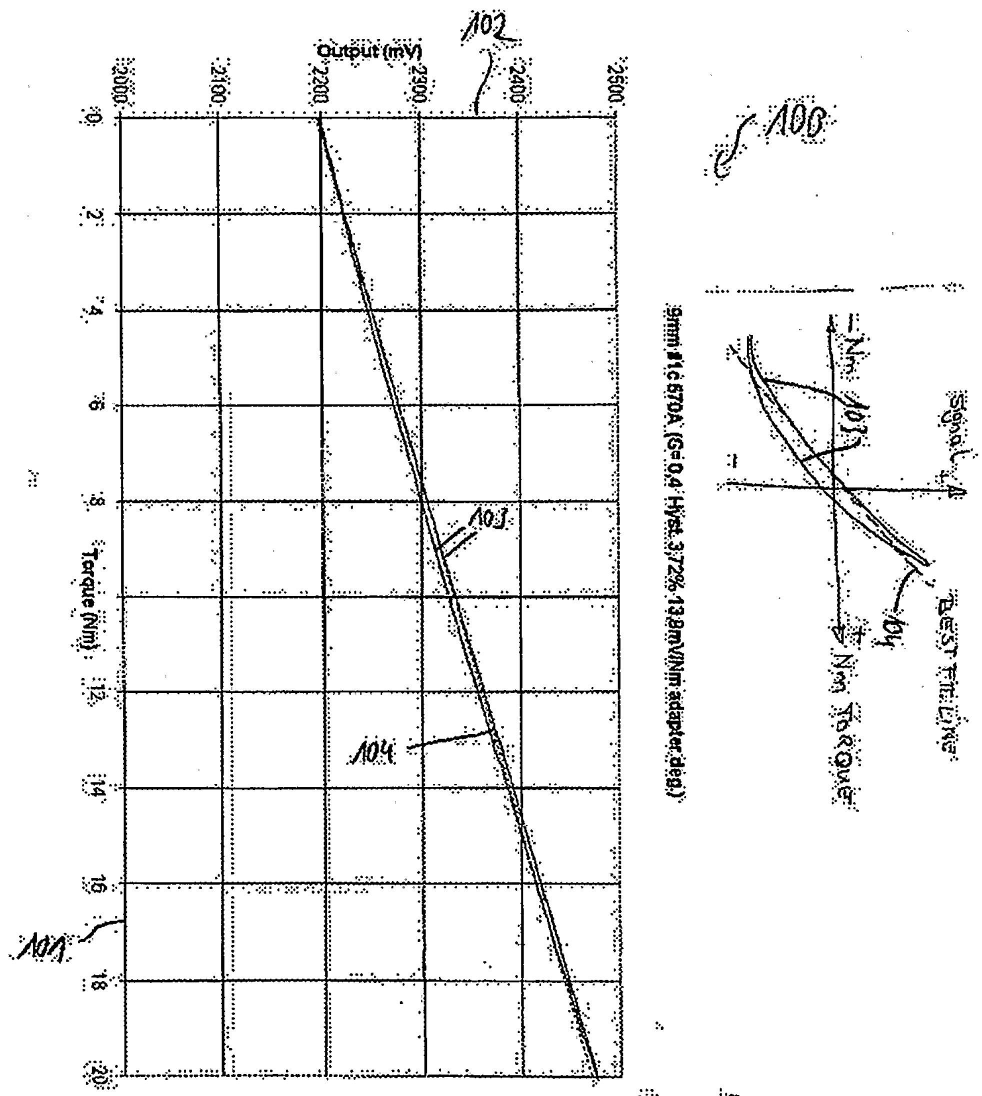
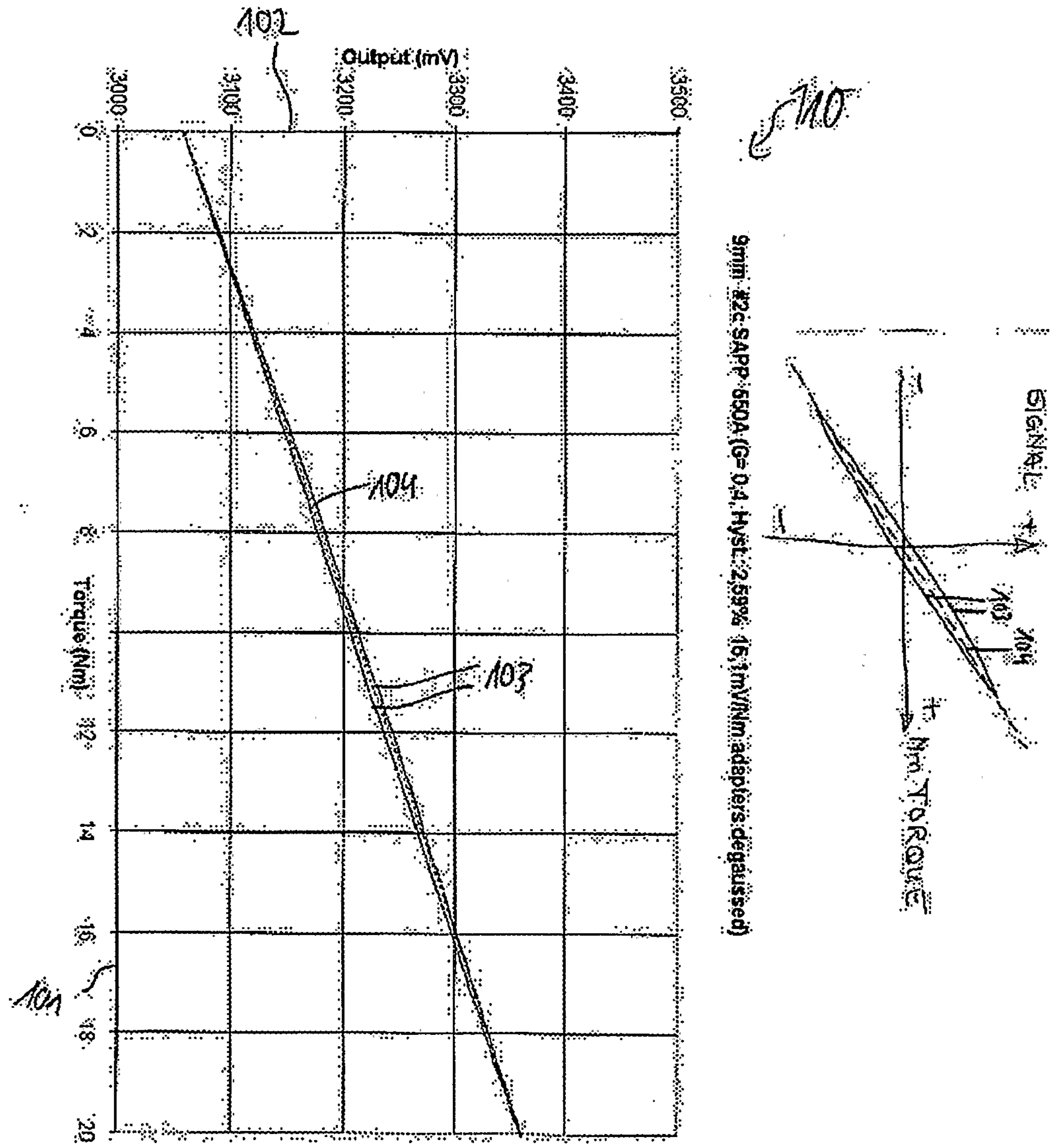

Output (mV)
2000
2100
2200
2300
2400
2500
Torque (Nm)
0
2
4
6
8
12
14
16
18
20
100
101
102
103
104
Signal
BEST FIT LINE
Nm TORQUE

Fig 1D



102
Output (mV)
3000
3100
3200
3300
3400
3500
110
0
2
4
6
8
Torque (Nm)
12
14
16
18
20
101
104
103
9mm #2c SAPP 650A (G= 0.4, Hyst. 2.59% 16.1mV/Nm adapters degaussed)
SIGNAL
+
-
103
104
Nm TORQUE

Fig 1E

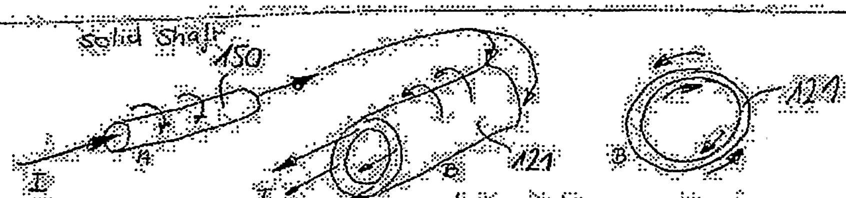


Fig 2

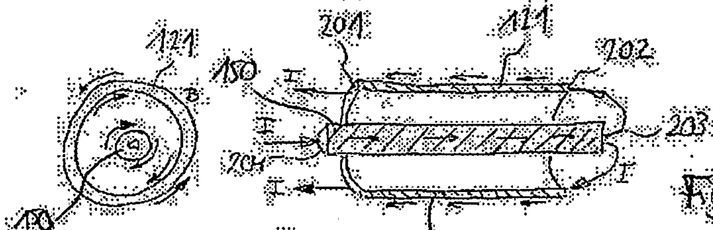


Fig 3A

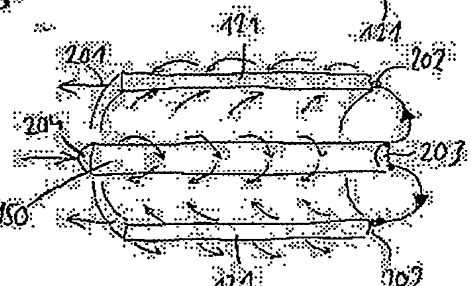


Fig 3B

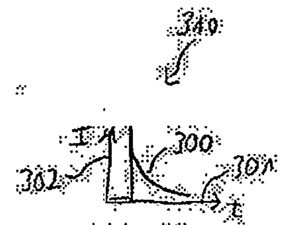


Fig 3D

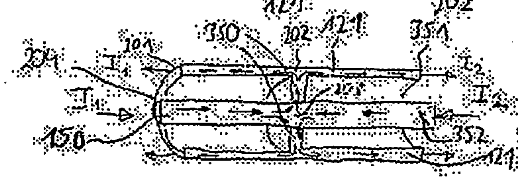


Fig 3C

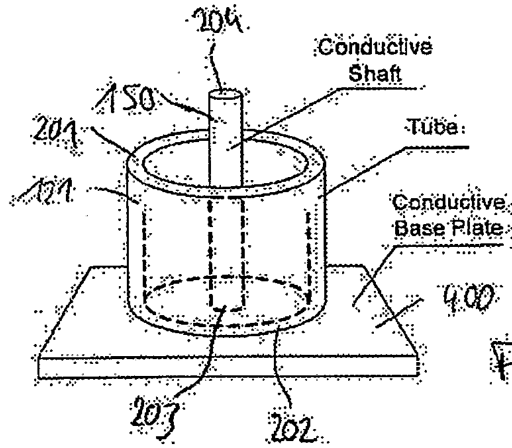

204
Conductive
Shaft
150
201
Tube
121
Conductive
Base Plate
400
203
202

Fig.4A

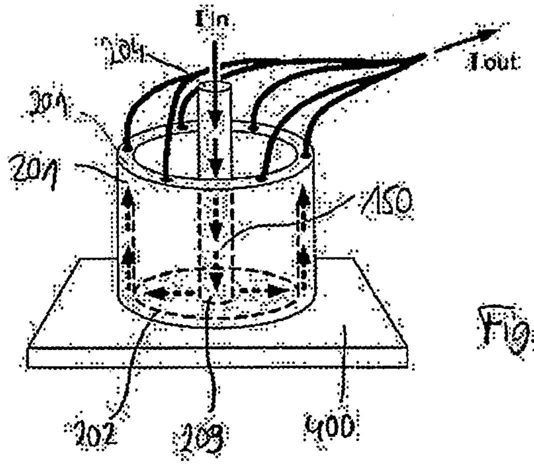

I in
204
I out
301
201
150
202
203
400

Fig.4B

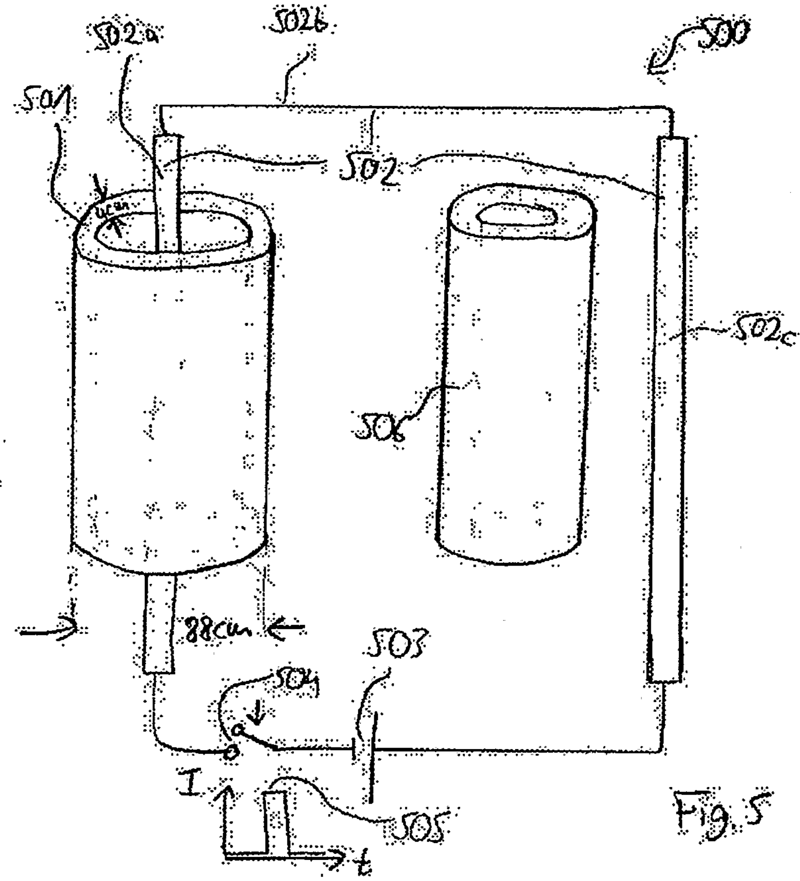

502a
502b
500
501
6cm
502
502c
506
88cm
503
504
I
505
t

Fig. 5

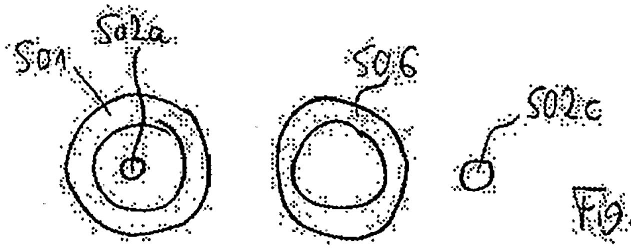

501
502a
506
502c

Fig. 6A

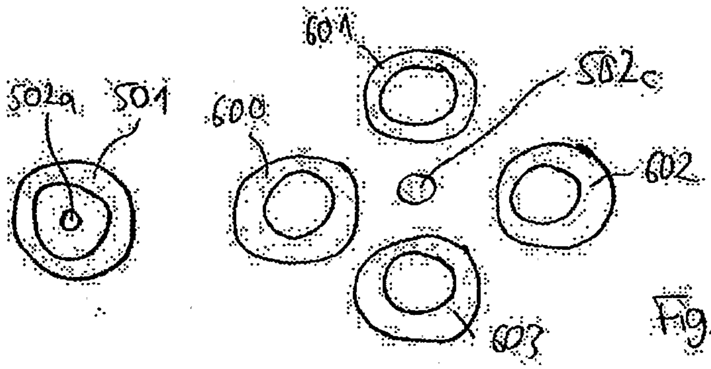


Fig. 6B

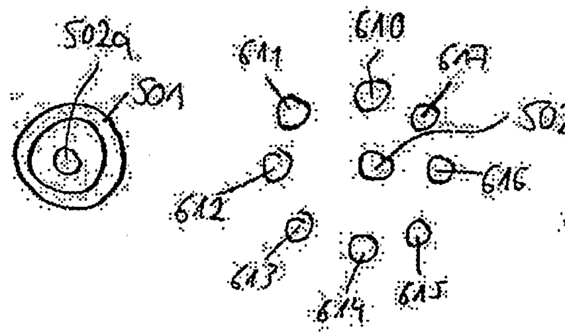


Fig. 6C

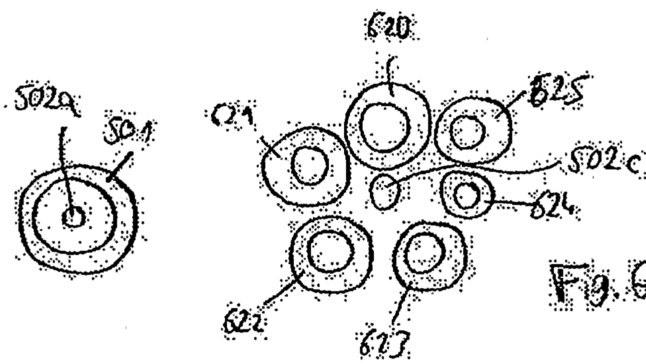


Fig. 6D

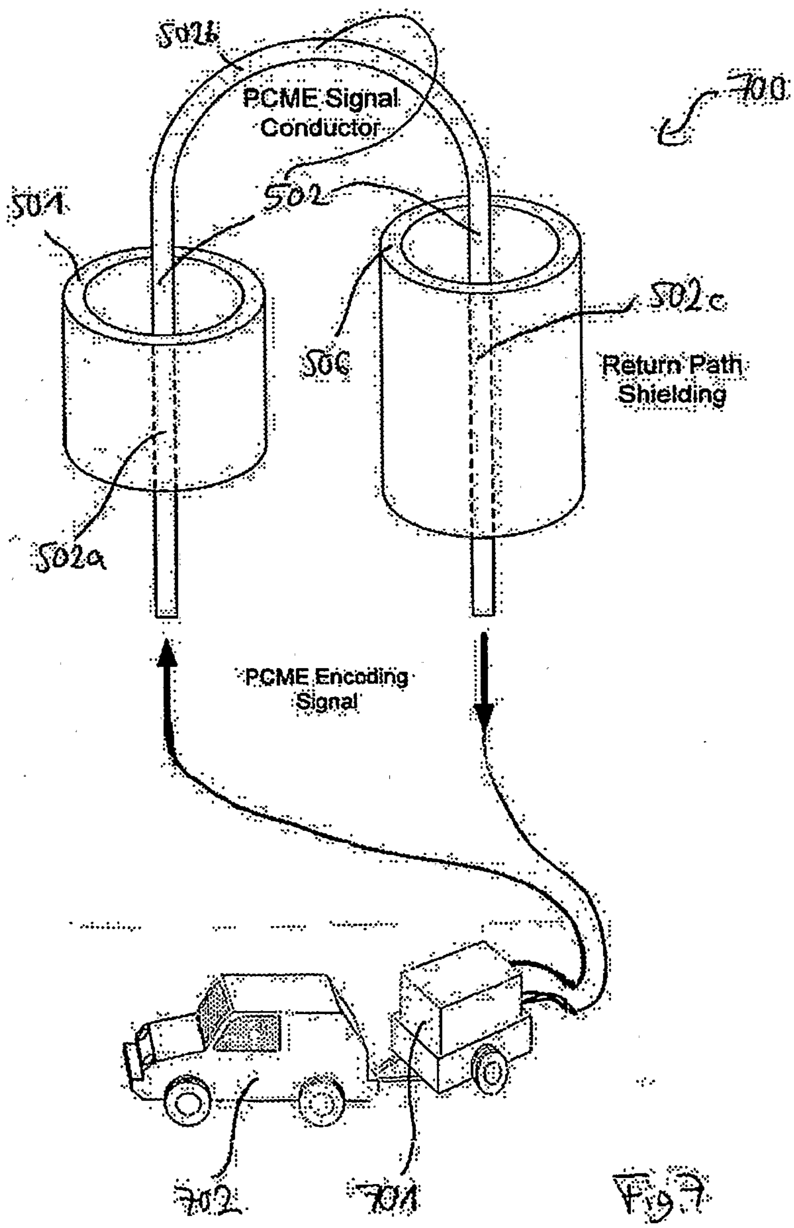
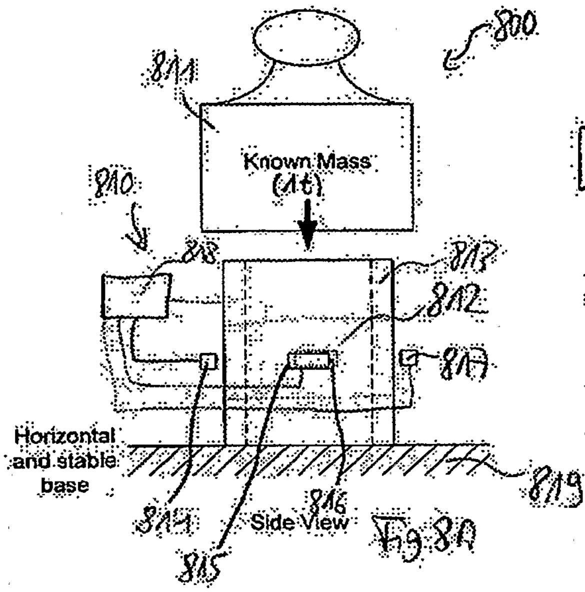
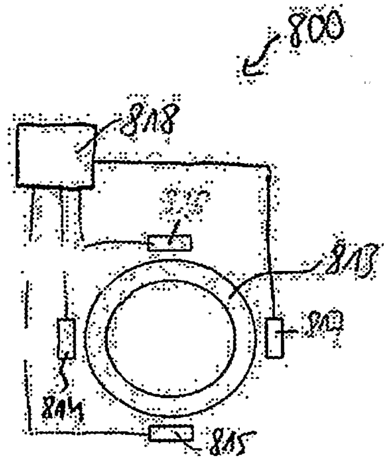

502b
PCME Signal
Conductor
700
501
502
502c
506
Return Path
Shielding
502a
PCME Encoding
Signal
702
701

Fig.7



Side View Fig.8A



Top View Fig. 8B

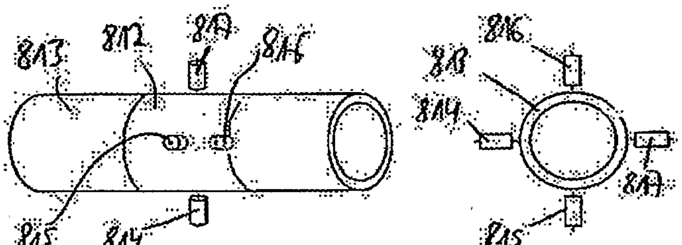


Fig.9A

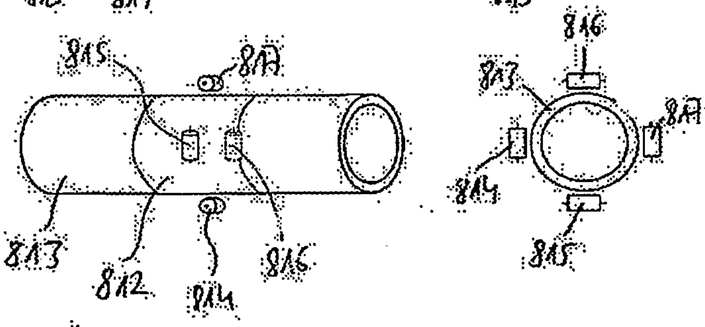


Fig.9B

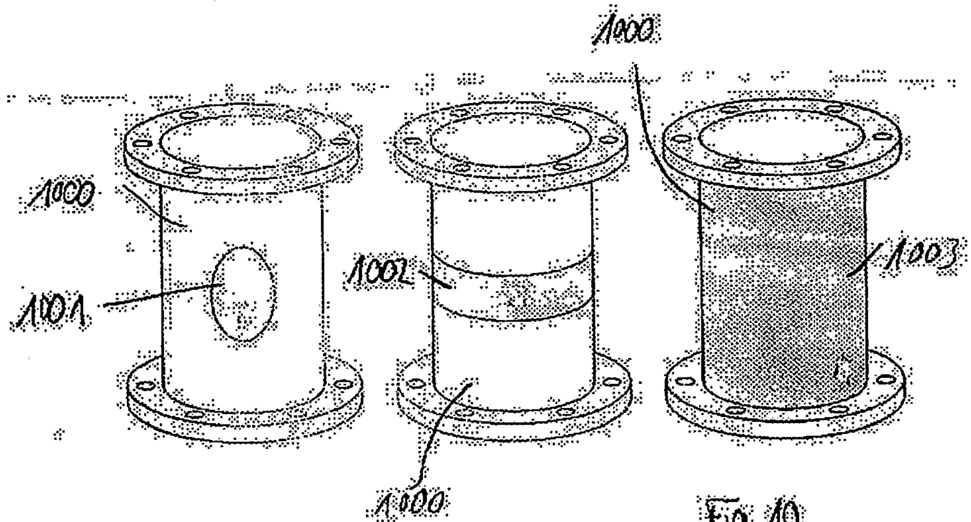

1000
1000
1001
1002
1003
1000

Fig 10

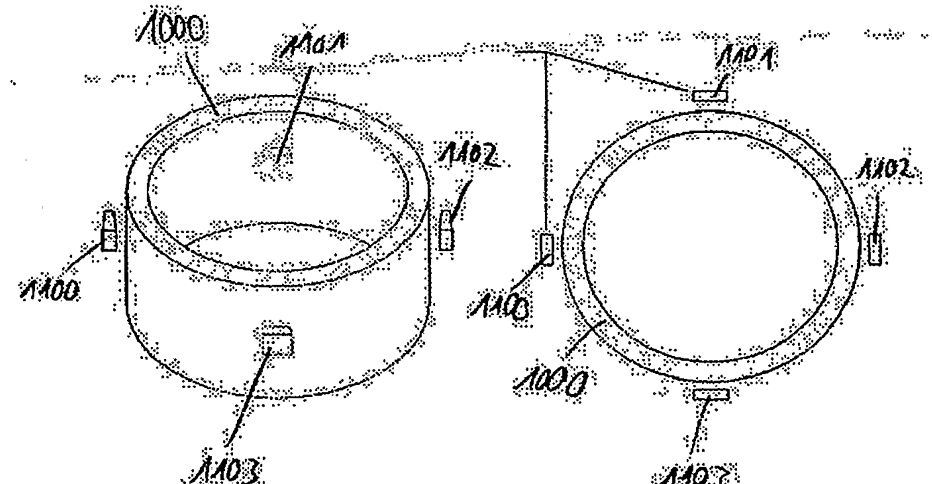

1000
1101
1101
1102
1102
1100
1100
1000
1103
1103

Fig 11

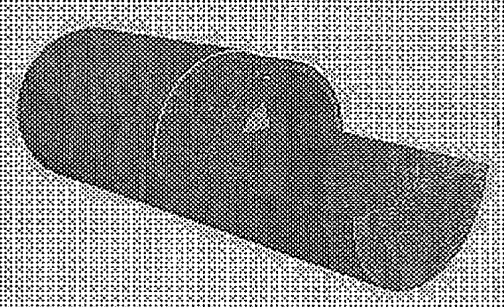


Fig 12

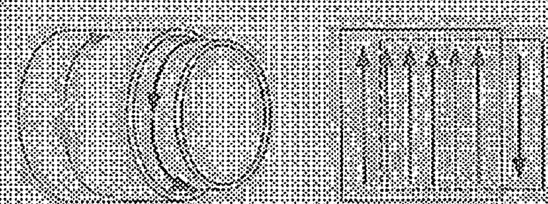
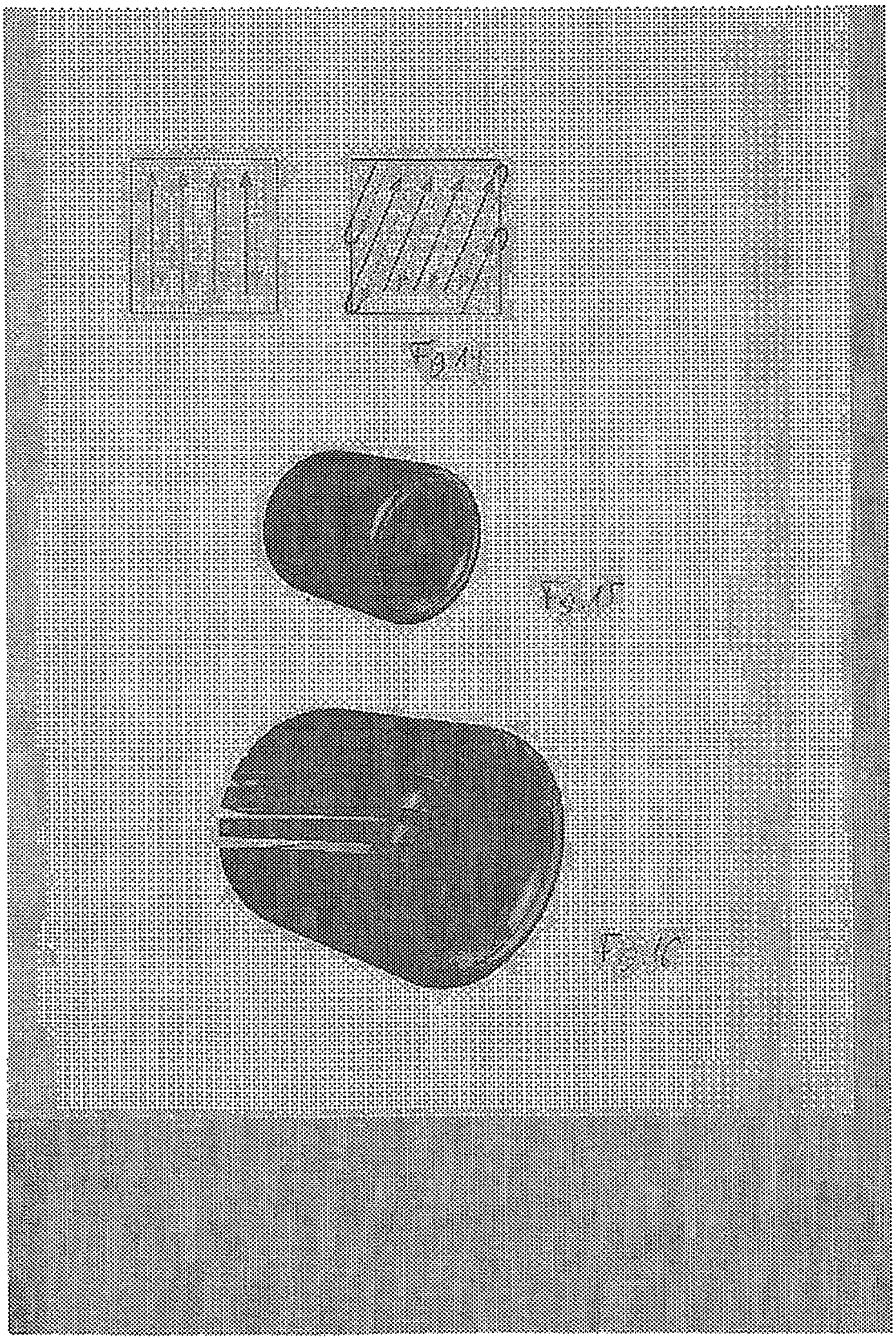


Fig 13



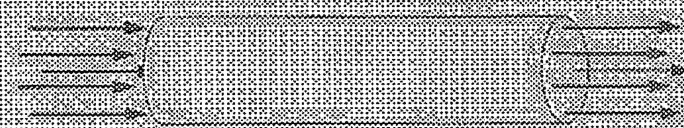


Fig. 17

Fig. 18

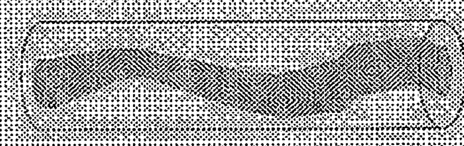


Fig. 19

Fig. 20

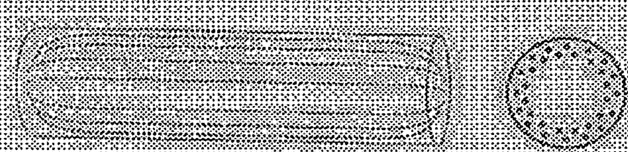


Fig 24

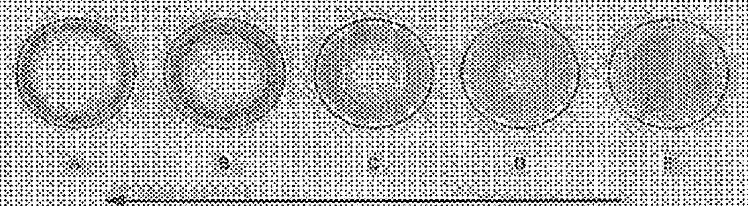


Fig 22

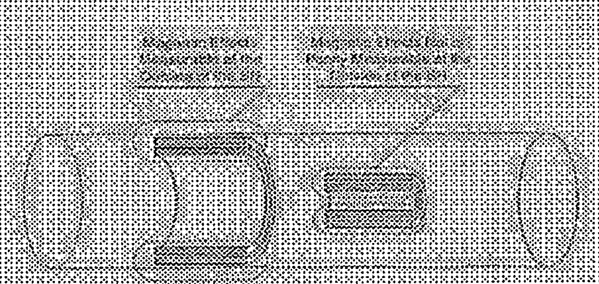
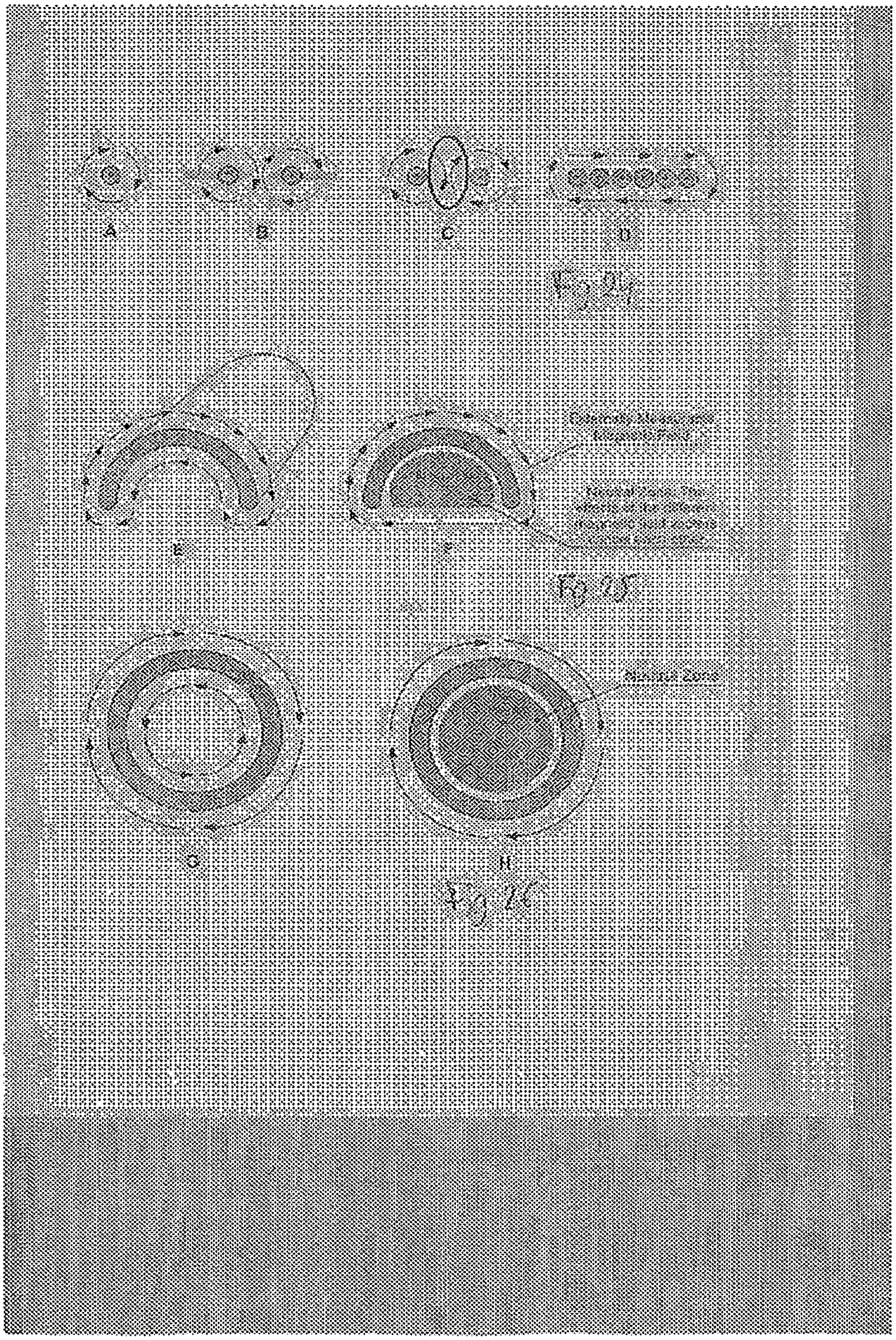


Fig 23


A
B
C
D
Fig 24
E
F
Fig 25
Mixing Zone
G
H
Fig 26

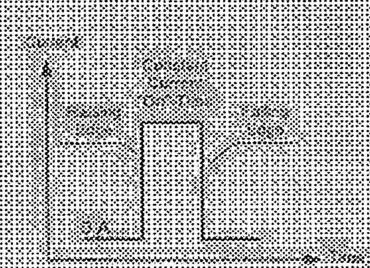


Fig 27

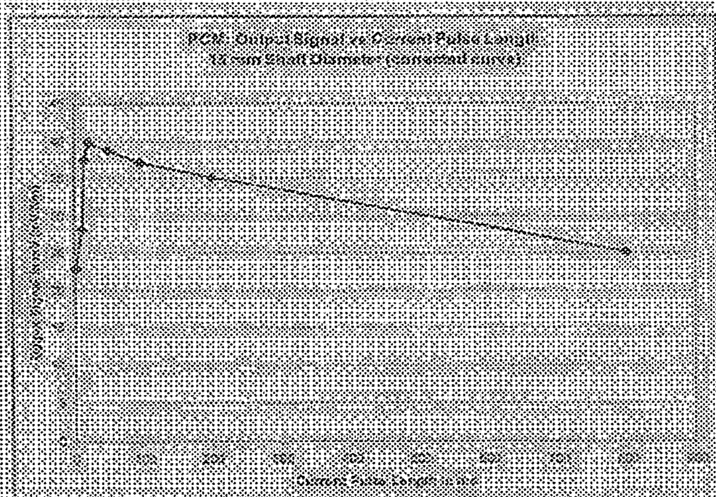


Fig 28

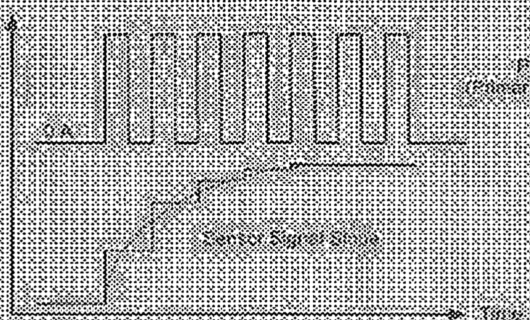


Fig 29

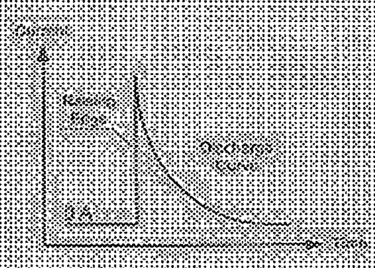


Fig 30

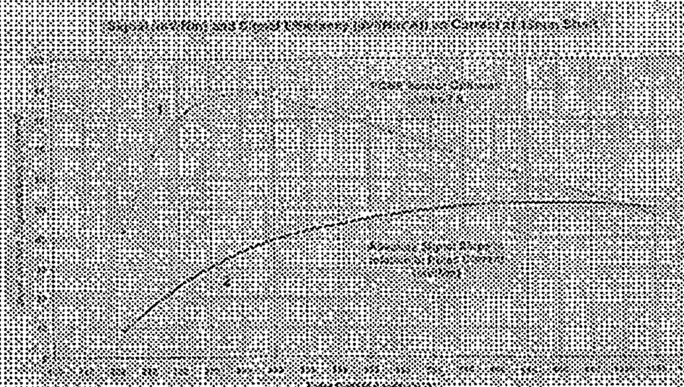


Fig 31

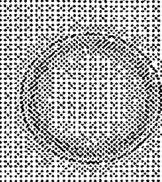


Fig 32

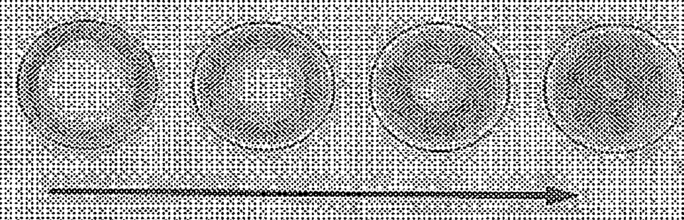


Fig 33

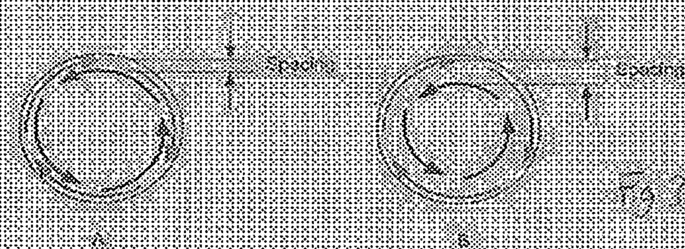


Fig 34

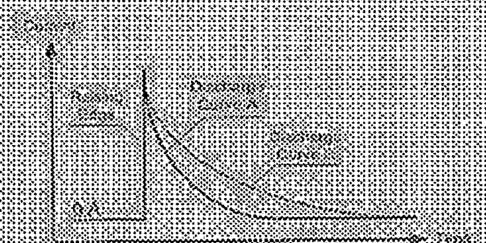
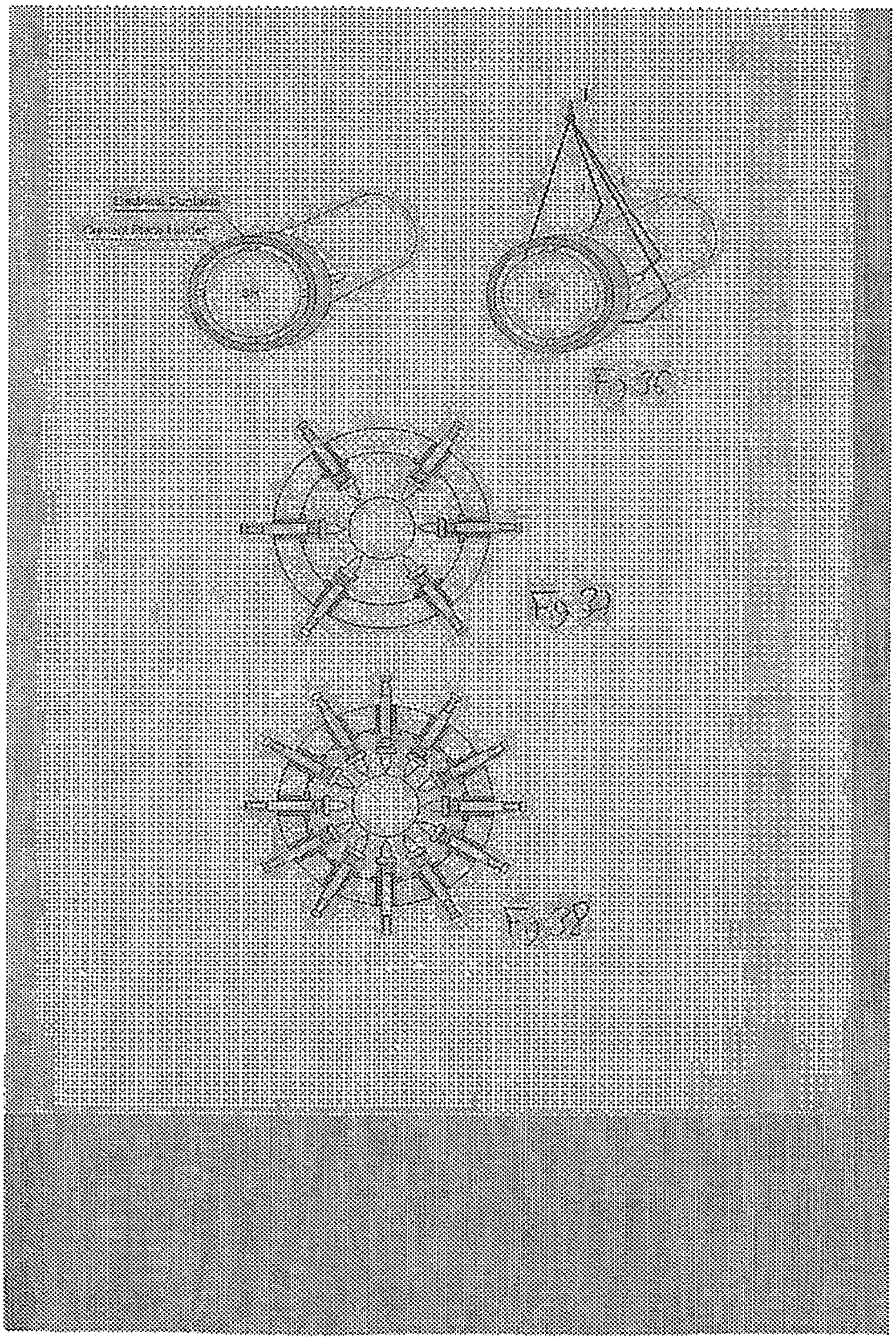
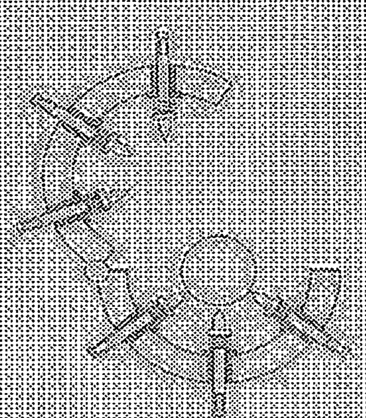


Fig 35





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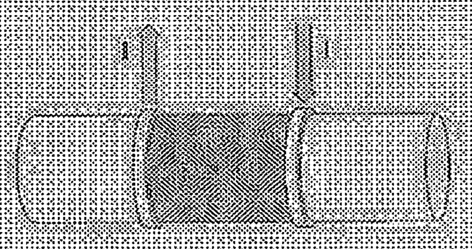


Fig 40

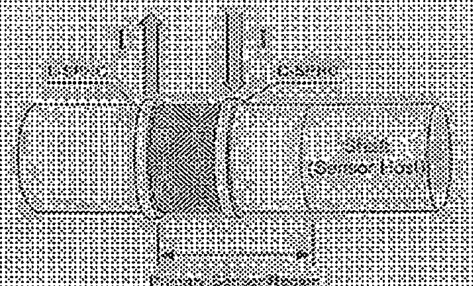


Fig 41

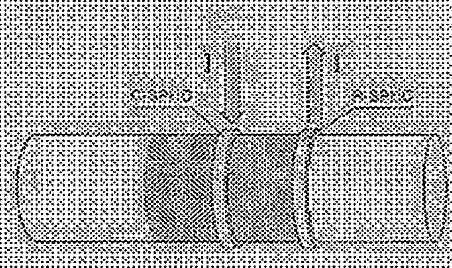


Fig 42

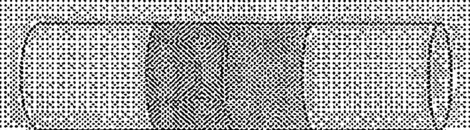


Fig 43

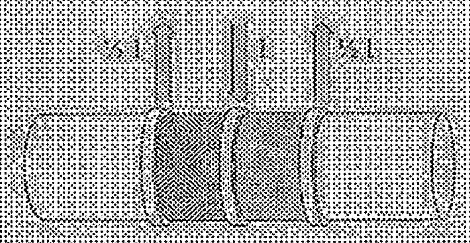


Fig 44

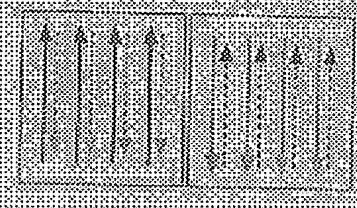


Fig 45

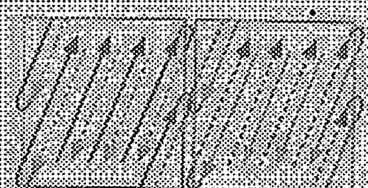


Fig 46

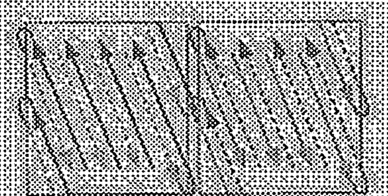
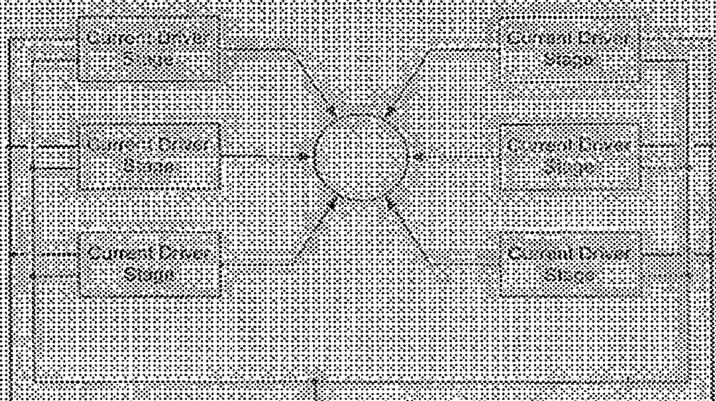
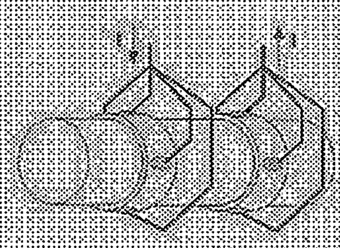


Fig 47


Current Driver Stage
Current Driver Stage
Current Driver Stage
Current Driver Stage
Current Driver Stage
Current Driver Stage
Signal Control
Supply



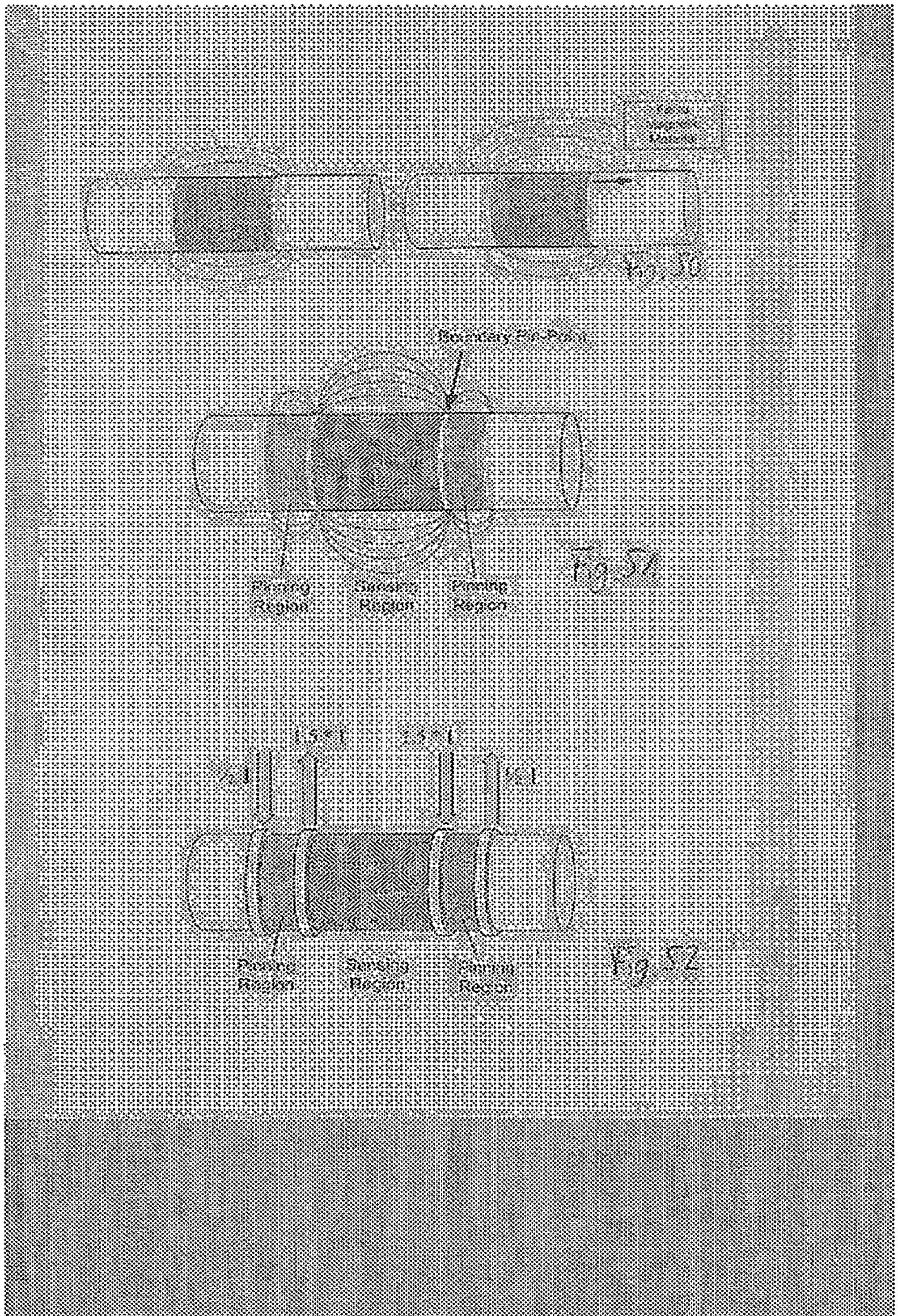


Fig. 50

Fig. 51

Fig. 52

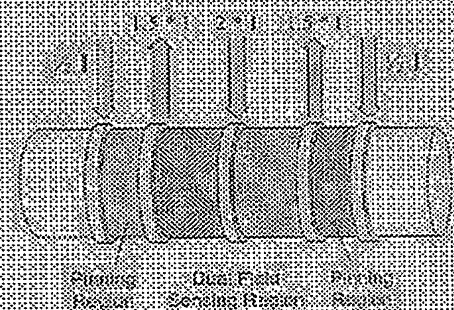


Fig. 53

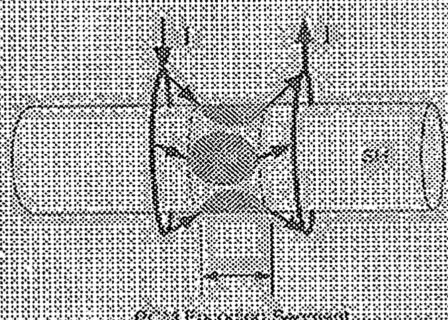


Fig. 54

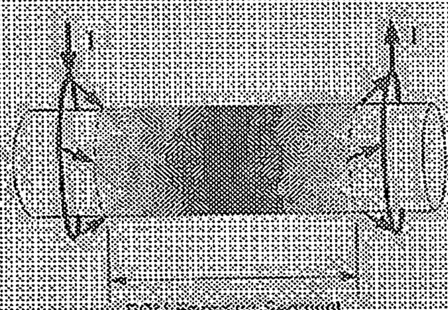


Fig. 55

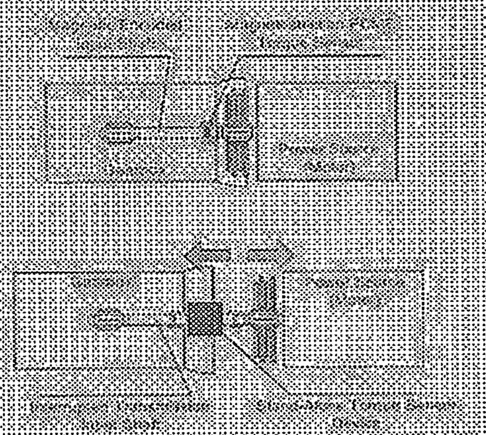


Fig 58

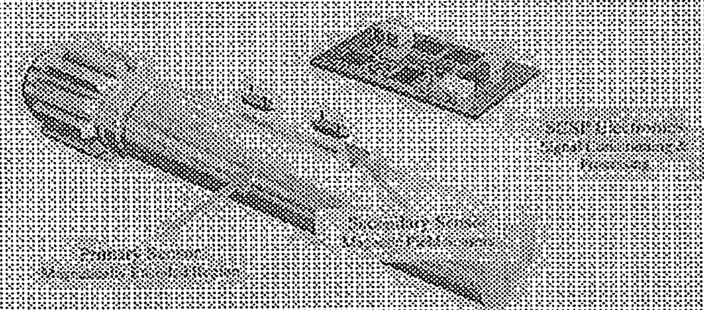


Fig 59

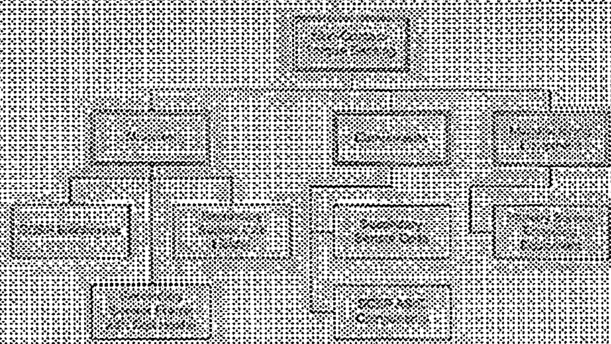


Fig. 58

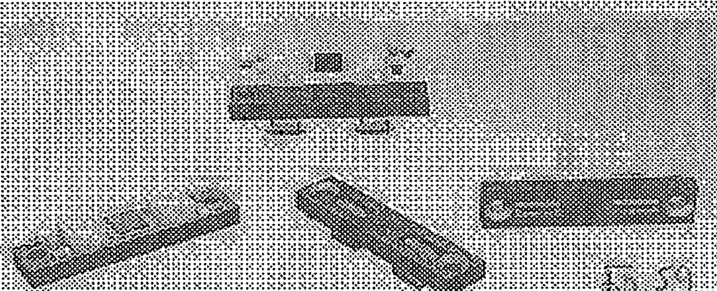


Fig. 59

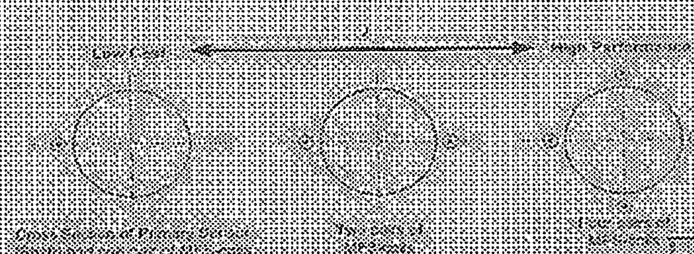


Fig. 60

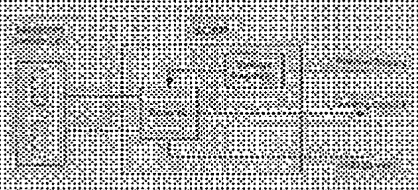


Fig 61

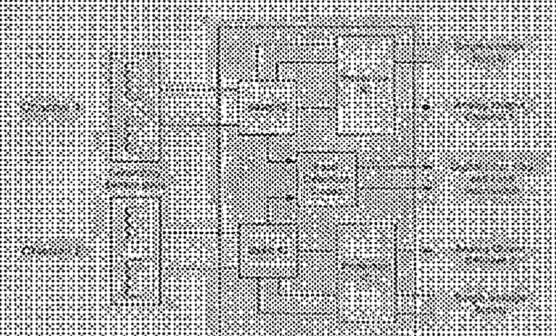
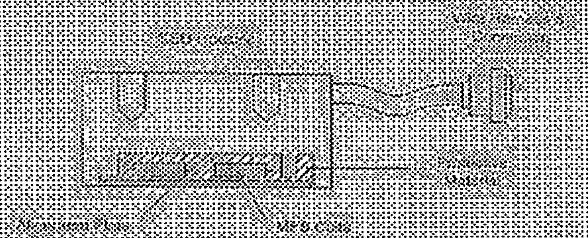
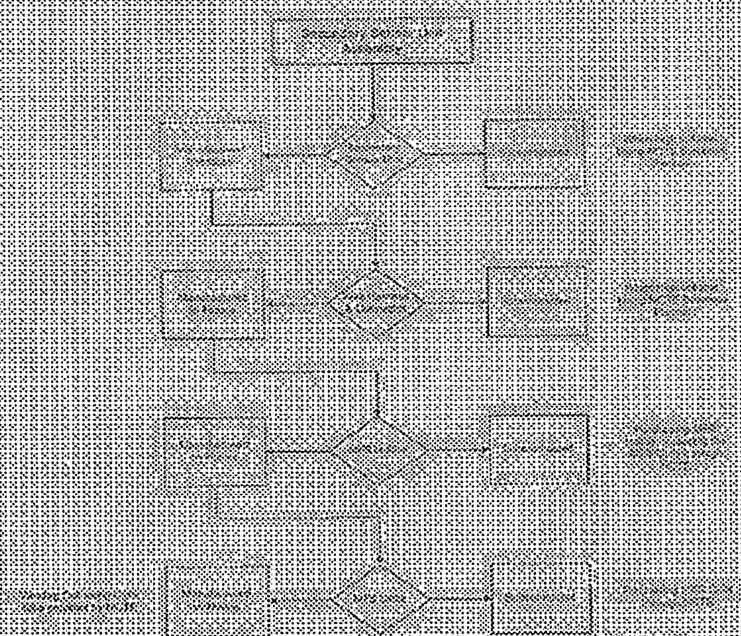
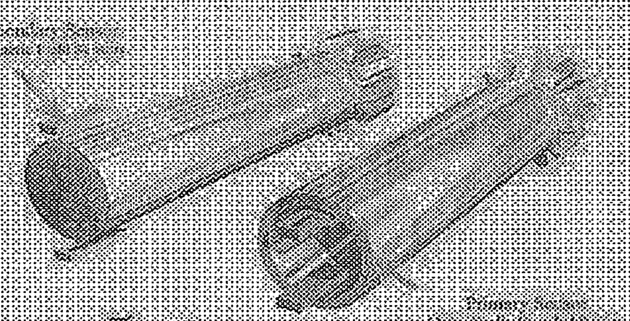


Fig 62







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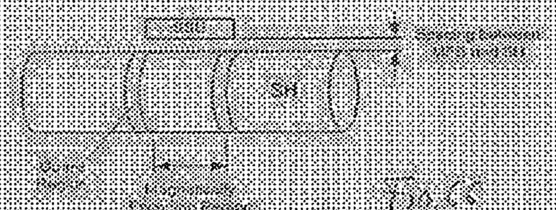

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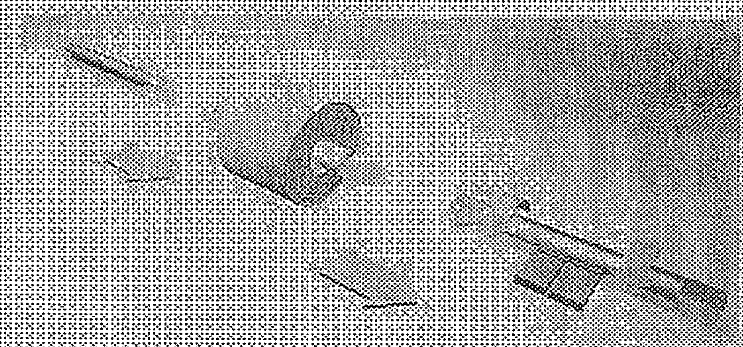

Fig 9

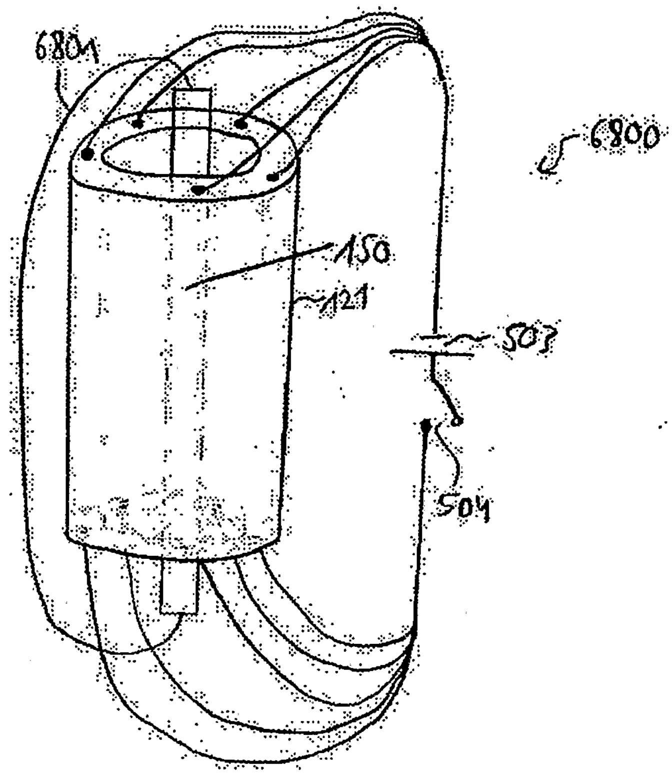

Fig 68

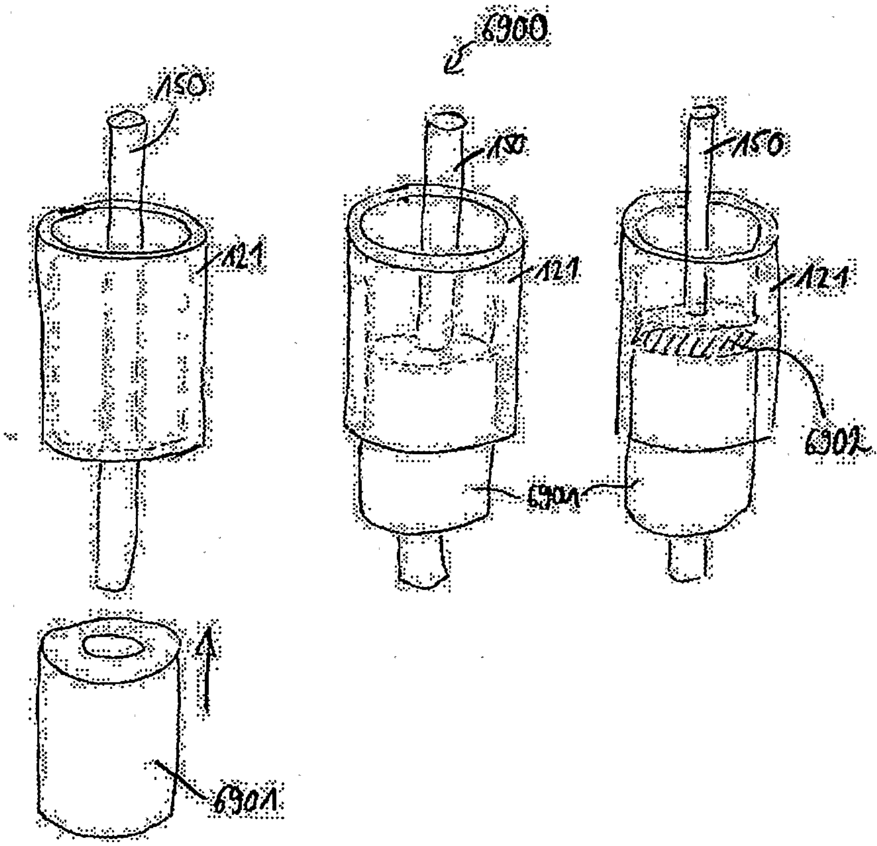

Fig 69

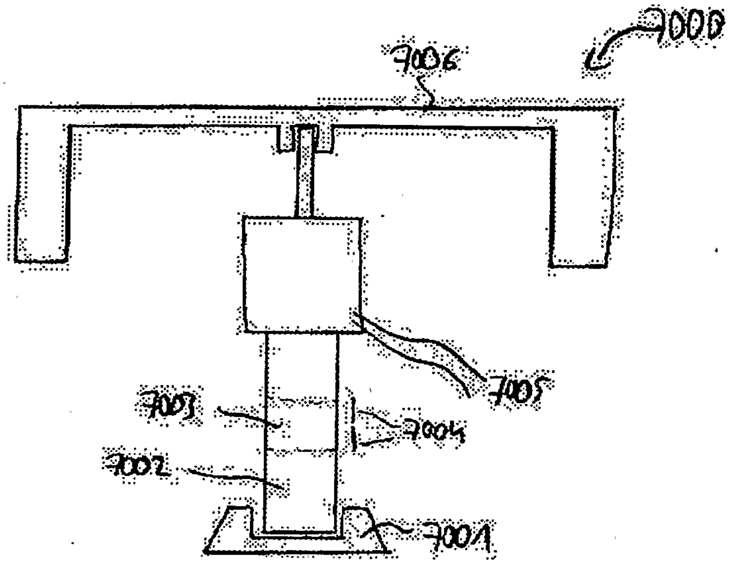

Fig 70

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PCT/EP2004/014797

25.02.05

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UNITED STATES DEPARTMENT OF COMMERCE

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February 09, 2005

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FILING DATE: *September 23, 2004*

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E. BORNETT

Certifying Officer

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Inventor(s)	:	**Lutz MAY** **Wolfratshauser Str. 23a** **82578 Geretsried-Gelting** **Germany** **Citizenship: Germany**
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For	:	**POSITION SENSOR DEVICE, A POSITION SENSOR ARRAY, A CONCRETE PROCESSING APPARATUS AND A METHOD FOR DETERMINING A POSITION OF A RECIPROCATING OBJECT**

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Name: Oleg F. Kaplun, Reg. No. 45,559

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Date: September 23, 2004

By: ______________________
Oleg F. Kaplun (Reg. No. 45,559)

Fay Kaplun & Marcin, LLP
150 Broadway, Suite 702
New York, NY 10038
Tel: 212-619-6000
Fax: 212-619-0276

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U.S. PROVISIONAL PATENT APPLICATION

For

POSITION SENSOR DEVICE, A POSITION SENSOR ARRAY, A CONCRETE PROCESSING APPARATUS AND A METHOD FOR DETERMINING A POSITION OF A RECIPROCATING OBJECT

Inventor(s):

Lutz MAY

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Represented by:

FAY KAPLUN & MARCIN, LLP

150 Broadway, Suite 702

New York, NY 10038

(212) 619-6000 (tel)

(212) 619-0276 (fax)

info@FKMiplaw.com

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Name: Oleg F. Kaplun, Reg. No. 45,559

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Application No.
New Application
NCTENGINEERING GMBH

Our Reference
N 7177 / AD

Munich,
23. September 2004

NCTEngineering GmbH
Otto-Hahn-Straße 24, 85521 Ottobrunn, Germany

Position sensor device, a position sensor array, a concrete processing apparatus and a method for determining a position of a reciprocating object

Background of the Invention

Field of the Invention

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Description of the Related Art

For many applications, it is desirable to accurately measure the position of a moving object. For instance, it is highly advantageous to know the position of a reciprocating object to accurately control the reciprocation in an efficient manner.

According to the prior art, an optical marker can be provided on a reciprocating object, and an optical measurement can be performed to estimate the position of the optical marker and thus a position of the reciprocating object. However, under critical circumstances and conditions such as a dirty environment, the optical marker may be covered by a layer of dirt and may become "invisible" for an optical detecting means.

Further, in case that the reciprocating object is located in a dirty environment, an optical marker can be abrased by friction between the reciprocating object and dirt particles.

Such a scenario of critical conditions is present, for instance, in the case of a concrete processing apparatus in which a reciprocating shaft mixes concrete and in which the position of the reciprocating shaft or work cylinder is desired to known to efficiently control the reciprocation cycle.

Alternatively, a mechanical marker, such as an engraving, can be used as a marker to detect the position or velocity of a reciprocating object. However, such an engraving structure may be filled or covered with dirt and is thus not appropriate to be implemented under critical and dirty conditions. A mechanical marker (engravings) may also present a challenge to maintain pneumatic or hydraulic sealing.

Summary of the Invention

It is an object of the present invention to enable an accurate position detection of a reciprocating object capable of being used under critical conditions like a dirty environment.

This object is achieved by providing a position sensor device, a position sensor array, a concrete processing apparatus and a method for determining a position of a reciprocating object according to independent aspects of the invention mentioned in the following.

In the following, different aspects of the invention will be described.

Aspects 1, 27, 33 and 37 are independent aspects of the invention which may be realized with or without any other means. Aspects 2 to 26 relate to preferred embodiments of aspect 1. Aspects 28 to 32 relate to preferred embodiments of aspect 2. Aspects 34 to 36 relate to preferred embodiments of aspect 3.

1. aspect: A position sensor device for determining a position of a reciprocating object, comprising:

at least one magnetically encoded region fixed on a reciprocating object;

at least one magnetic field detector;

a position determining unit;

wherein the magnetic field detector is adapted to detect a signal generated by the magnetically encoded region when the magnetically encoded region reciprocating with the reciprocating object passes a surrounding area of the magnetic field detector;

wherein the position determining unit is adapted to determine a position of a reciprocating object based on the detected magnetic signal.

2. aspect: The position sensor device according to aspect 1,

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wherein the at least one magnetically encoded region is a permanent magnetic region.

3. aspect: The position sensor device according to aspect 1 or 2,
wherein the at least one magnetically encoded region is a longitudinally magnetized region of the reciprocating object.

4. aspect: The position sensor device according to aspect 1 or 2,
wherein the at least one magnetically encoded region is a circumferentially magnetized region of the reciprocating object.

5. aspect: The position sensor device according to any of aspects 1, 2 or 4,
wherein the at least one magnetically encoded region is formed by a first magnetic flow region oriented in a first direction and by a second magnetic flow region oriented in a second direction, wherein the first direction is opposite to the second direction.

6. aspect: The position sensor device according to aspect 5,
wherein, in a cross-sectional view of the reciprocating object, there is the first circular magnetic flow having the first direction and a first radius and the second circular magnetic flow having the second direction and a second radius, wherein the first radius is larger than the second radius.

7. aspect: The position sensor device according to aspect 1 or 2,
wherein the at least one magnetically encoded region is a magnetic element attached to the surface of the reciprocating object.

8. aspect: The position sensor device according to any of aspects 1 to 7,
wherein the at least one magnetic field detector comprises at least one of the group consisting of

a coil having a coil axis oriented essentially parallel to a reciprocating direction of the reciprocating object;

a coil having a coil axis oriented essentially perpendicular to a reciprocating direction of the reciprocating object;

a Hall-effect probe;

a Giant Magnetic Resonance magnetic field sensor; and

a Magnetic Resonance magnetic field sensor.

9. aspect: The position sensor device according to any of aspects 1 to 8,
comprising a plurality of magnetically encoded regions fixed on the reciprocating object.

10. aspect: The position sensor device according to aspect 9,
wherein the plurality of magnetically encoded regions are arranged on the reciprocating object at constant distances from one another.

11. aspect: The position sensor device according to aspect 9,
wherein the plurality of magnetically encoded regions are arranged on the reciprocating object at different distances from one another.

12. aspect: The position sensor device according to aspect 11,
wherein the different distances are selected based on a linear function, a logarithmic function or a power function.

13. aspect: The position sensor device according to any of aspects 9 to 12,
wherein the plurality of magnetically encoded regions are arranged on the reciprocating object with constant dimensions.

14. aspect: The position sensor device according to any of aspects 9 to 12,

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wherein the plurality of magnetically encoded regions are arranged on the reciprocating object with different dimensions.

15. aspect: The position sensor device according to any of aspects 9 to 14, wherein different magnetically encoded regions are provided of different magnetic materials.

16. aspect: The position sensor device according to any of aspects 9 to 15, wherein different magnetically encoded regions are provided with different values of magnetization.

17. aspect: The position sensor device according to any of aspects 1 to 16, comprising a plurality of magnetic field detectors.

18. aspect: The position sensor device according to any of aspects 1 to 17, wherein the plurality of magnetic field detectors are arranged along the reciprocating object at constant distances from one another.

19. aspect: The position sensor device according to any of aspects 1 to 17, wherein the plurality of magnetic field detector are arranged along the reciprocating object at different distances from one another.

20. aspect: The position sensor device according to aspect 19, wherein the different distances are selected based on a linear function, a logarithmic function or a power function.

21. aspect: The position sensor device according to any of aspects 1 to 20,

comprising a plurality of magnetically encoded regions fixed on the reciprocating object; and

comprising a plurality of magnetic field detectors.

22. aspect: The position sensor device according to aspect 21,
wherein the arrangement of the plurality of magnetically encoded regions along the reciprocating object corresponds to the arrangement of the plurality of magnetic field detectors.

23. aspect: The position sensor device according to aspect 22,
wherein at least a part of the plurality of magnetic field detectors are arranged displaced from an arrangement of a corresponding one of the plurality of magnetically encoded regions arranged along the reciprocating object.

24. aspect: The position sensor device according to any of aspects 1 to 23,
wherein the number of the magnetically encoded regions equals the number of magnetic field detectors.

25. aspect: The position sensor device according to any of aspects 1 to 23,
wherein the number of the magnetically encoded regions differs from the number of magnetic field detectors.

26. aspect: The position sensor device according to any of aspects 1 to 25,
wherein the reciprocating object is a push-pull-rod in a gearbox of a vehicle.

27. aspect: A position sensor array, comprising
a reciprocating object; and
a position sensor device according to any of aspects 1 to 26 for determining a position of the reciprocating object.

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28. aspect: The position sensor array according to aspect 27, wherein the reciprocating object is a shaft.

29. aspect: The position sensor array according to aspect 27 or 28, wherein the magnetically encoded region is provided along a part of the length of the reciprocating object.

30. aspect: The position sensor array according to aspect 27 or 28, wherein the magnetically encoded region is provided along the entire length of the reciprocating object.

31. aspect: The position sensor array according to any of aspects 27 to 29, wherein the reciprocating object is divided into a plurality of equally spaced segments, each segment comprising one magnetically encoded region, the magnetically encoded regions of the segments being arranged in an asymmetric manner.

32. aspect: The position sensor array according to any of aspects 27 to 31, further comprising a control unit adapted to control the reciprocation of the reciprocating object based on the position of the reciprocating object which is provided to the control unit by the position sensor device.

33. aspect: A concrete processing apparatus, comprising

a concrete processing chamber;

a reciprocating shaft arranged in the concrete processing chamber adapted to reciprocate to mix concrete; and

a position sensor device according to any of aspects 1 to 27 adapted to determine a position of the reciprocating shaft.

34. aspect: The concrete processing apparatus according to aspect 33, further comprising a control unit adapted to control the reciprocation of the reciprocating shaft based on the position of the reciprocating shaft which is provided to the control unit by the position sensor device.

35. aspect: The concrete processing apparatus according to aspect 33 or 34, further comprising a vehicle on which the concrete processing chamber, the reciprocating shaft and the position sensor device are mounted.

36. aspect: The concrete processing apparatus according to any of aspects 33 to 35,

comprising a further reciprocating shaft arranged in the concrete processing chamber adapted to reciprocate to mix concrete;

wherein the reciprocating shaft and the further reciprocating shaft are operable in a countercyclical manner.

37. aspect: A method for determining a position of a reciprocating object, comprising the steps of

detecting a signal by a magnetic field detector, the signal being generated by a magnetically encoded region fixed on a reciprocating object when the magnetically encoded region reciprocating with the reciprocating object passes a surrounding area of the magnetic field detector;

determining a position of a reciprocating object based on the detected signal.

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In the following, the above mentioned independent aspects of the invention will be described in more detail.

One idea of the invention may be seen in the aspect to enable accurate position detection of a reciprocating object, such as a reciprocating working cylinder of a concrete (or cement) processing apparatus, by providing one or more magnetically encoded regions on the reciprocating object. When the reciprocating object reciprocates, the magnetically encoded region passes – from time to time - an area of sensitivity/a sufficient close vicinity of a magnetic field detector so that a counter electromotive force may be generated in a magnetic coil as a magnetic field detector by which the presence of the magnetically encoded region can be detected. Since the position of the magnetically encoded regions on the reciprocating object is known or can be predetermined, the determining unit can derive from the detected signal the actual position of the reciprocating object. To determine the position of the reciprocating object from the detected signal, correlation information can be taken into account. Such correlation information can be pre-stored in a memory device coupled with the position determining unit and may correlate the presence of a particular signal of a particular magnetically encoded region with a corresponding position of the shaft. In other words, correlation information correlates a detected (electrical) signal with a position of the object.

"Position" in the context of this description particularly means the information that a particular region or point of the reciprocating object is located at a determined position at a particular point of time.

The fact that the magnetically encoded region is fixed on the reciprocating object means that it may be integrated as a part of the object or alternatively may be attached as an external element to the surface of the object.

Particularly, one or more magnetically encoded regions can be formed on different portions of a hydraulic work cylinder, wherein each of magnetic field detector(s) senses a detecting signal each time a magnetically encoded region traverses a sphere of sensitivity of the magnetic field detector. Thus, the position, the velocity, the acceleration, and so on, of the working cylinder can be estimated with high accuracy, wherein this information can be used to drive the cylinder in a controlled manner to optimize its function.

Since the detection principle of the invention is contactless, the detection is not disturbed by friction effects and does not require a dirt-free environment. Thus, the invention particularly may advantageously be applied in technical fields in which a dirty environment may occur, for instance as a position detecting apparatus for a reciprocating shaft in a concrete processing apparatus, in the field of oil boring, and in the field of mining.

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Further, the magnetic position detecting principle of the invention can be manufactured with low effort, is easy to handle and can be applied to any existing shaft by magnetizing a part of the shaft using a method which will described in detail below (PCME, "Pulse-Current-Modulated Encoding"). For instance, many industrial steels used for shafts of an engine or a work cylinder can be magnetized to form a magnetically encoded region of the invention. The detection principle of the invention is very sensitive and provides a good signal to noise ratio. The invention can be applied to reciprocating objects like a reciprocating shaft having a full scale measurement range preferably in the range of 1 millimetre to 1 meter, but which may be less than 1 millimetre, or which may be as much as 1 (or more) meters.

The invention particularly allows to identify certain (absolute) positions (or fix points) on a reciprocating object, like the position where a pump or generator has to be shut off (on-off function). This invention can also be used to make a precise measurement at a specific range on a reciprocating object (defining a linear position on an object).

While different types of linear positioning sensors (the concept of which differ fundamentally from the concept of the invention) exist in large quantities and that for a relative long time, this particular invention is particularly designed to function under harsh and abrasive conditions where most other technologies will fail.

A very important aspect of a PCME based linear position sensing technology according to a preferred embodiment of the invention is that the magnetic pick-up device may be very small and therefore can be easily placed in small spaces, like inside of a sealing chamber in a pneumatic or hydraulic device.

Another benefit is that the magnetic field emanating from the permanent magnetic markers is relatively small and therefore will not attract metallic particles. A typical magnetic proximity sensor (like an automotive wheel-speed sensor) uses very strong magnetic field to function reliable. Therefore ferromagnetic particles will stick on the surface of such sensors which is why they cannot be used in dirty environments.

The technology of the invention may be also used, in the frame of a concrete processing apparatus, to control the hydraulic cylinder position of the crane arm that carries the mixed and still liquid concrete mass through a long and flexible pipe to a specific location at a building site.

The hydraulic cylinders need to be extended or contracted so that the height and position of the crane arm can be changed. The PCME magnetic markers are appropriate to identify the exact position at the cylinder and to detect vibrations or oscillations that are caused by the concrete pump and the pulsing semi-liquid mass in the flexible pipe.

When the crane arm is pulsing/vibrating to much then the pump has to change its operation to prevent a problem (crane arm is moving outside of the acceptable position tolerance).

In the following, preferred embodiments of the position sensor device according to the first independent aspect of the invention will be described. However, these embodiments also apply for the position sensor array, the concrete processing apparatus and the method for determining a position of a reciprocating object according to other independent aspects of the invention.

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The at least one magnetically encoded region of the position sensor device may be a permanent magnetic region. The term "permanent magnetic region" refers to a magnetized material which has a remaining magnetization also in the absence of an external magnetic field. Thus, "permanent magnetic materials include ferromagnetic materials, ferrimagnetic materials, or the like. The material of such a magnetic region may be a 3d-ferromagnetic material like iron, nickel or cobalt, or may be a rare earth material (4f-magnetism).

The at least one magnetically encoded region may be a longitudinally magnetized region of the reciprocating object. Thus, the magnetizing direction of the magnetically encoded region may be oriented along the reciprocating direction of the reciprocating object. A method of manufacturing such a longitudinally magnetized region is disclosed, in a different context, in WO 02/063262 A1, and uses a separate magnetizing coil.

Alternatively, the at least one magnetically encoded region may be a circumferentially magnetized region of the reciprocating object. Such a circumferentially magnetized region may particularly be adapted such that the at least one magnetically encoded region is formed by a first magnetic flow region oriented in a first direction and by a second magnetic flow region oriented in a second direction, wherein the first direction is opposite to the second direction.

Thus, the magnetically encoded region may be realized as two hollow cylinder-like structures which are oriented concentrically, wherein the magnetizing directions of the two

concentrically arranged magnetic flow regions are preferably essentially perpendicular to one another. Such a magnetic structure can be manufactured by the PCME method described below in detail, i.e. by directly applying a magnetizing electrical current to the reciprocating object made of a magnetizable material. To produce the two opposing magnetizing flow portions, current pulses can be applied to the shaft.

Referring to the described embodiment, in a cross-sectional view of the reciprocating object, there may be a first (circular) magnetic flow having the first direction and a first radius and the second (circular) magnetic flow having the second direction and a second radius, wherein the first radius is larger than the second radius.

Alternatively, the at least one magnetically encoded region may be a (separate) magnetic element attached to the surface of the reciprocating object. Thus, an external element can be attached to the surface of the reciprocating object in order to form a magnetically encoded region. Such a magnetic element can be attached to the reciprocating object by adhered it (e.g. using glue), or may alternatively be fixed on the reciprocating shaft using the magnetic forces of the magnetic element.

Instead of attaching a magnetic object to the surface of the reciprocating object, it is also possible to use materials with different magnetic properties (one material has a higher, and the other a lower permeability, for example). The magnetic object can be attached from the outside of the shaft/cylinder or can be placed inside of the cylinder.

When using materials of different permeabilities, then an additional magnetic encoding of the shaft or cylinder is no longer necessary. An external magnetic source can be used (in

conjunction with the magnetic pick-up device) to detect when the magnetic flux is changing as a consequence of the moving shaft.

Any of the magnetic field detectors may comprise a coil having a coil axis oriented essentially parallel to a reciprocating direction of the reciprocating object. Further, any of the magnetic field detectors may be realized by a coil having a coil axis oriented essentially perpendicular to a reciprocating direction of the reciprocating object. A coil being oriented with any other angle between coil axis and reciprocating direction is possible and falls under the scope of the invention. Alternatively to a coil in which the moving magnetically encoded region may induce an induction voltage by modulating the magnetic flow through the coil, a Hall-effect probe may be used as magnetic field detector making use of the Hall effect. Alternatively, a Giant Magnetic Resonance magnetic field sensor or a Magnetic Resonance magnetic field sensor may be used as a magnetic field detector. However, any other magnetic field detector may be used to detect the presence or absence of one of the magnetically encoded regions in a sufficient close vicinity to the respective magnetic field detector.

Preferably, a plurality of magnetically encoded regions may be fixed on the reciprocating object. By providing a plurality of magnetically encoded regions, a number of fixed points on the reciprocating shaft are defined which may be detected separately so that the number of detection signals is increased. Consequently, the sensitivity and the accuracy of the position detection may be improved.

The plurality of magnetically encoded regions may be arranged on the reciprocating object at constant distances from one another. Thus, each time one of the magnetically encoded regions passes one of the magnetic field detectors, the reciprocating object has moved by a distance which equals the distance between the magnetically encoded regions. Thus, the position of the reciprocating shaft can be estimated in a time-dependent manner with high accuracy.

Alternatively, the plurality of magnetically encoded regions may be arranged on the reciprocating object at different distances from one another. For instance, the different distances may be selectively based on a linear function, on a logarithmic function or by a power function (for instance a power of two or of three). Thus, the time between the detection of subsequent signals by one of the magnetic field detectors follows the mathematical function according to which the magnetic encoding regions of the invention are separated from one another. This allows a unique assignment of the present position of the reciprocating object.

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Such a mathematical function can be a positive (increasing) function or a negative (decreasing) function, meaning that the spacing can become larger from one to the next magnetic marker, or it can become smaller from one to the next.

The plurality of magnetically encoded regions may be arranged on the reciprocating object with constant dimensions. A constant dimension (e.g. constant width, constant thickness, etc.) yields signals of a constant length in time as detected by any of the magnetic field detectors. However, in a scenario in which the reciprocating object reciprocates with a non-constant velocity, the length of the signals will change, so that velocity and acceleration information can be determined from the length of the signal in time.

Alternatively, the plurality of magnetically encoded regions may be arranged on the reciprocating object with different dimensions. This, similar to the case of providing the magnetically encoded regions at different distances from one another, allows a unique assignment of the magnetically encoded region which presently passes one of the magnetic field detectors.

Thus, the magnetic markers can be either all of the same physical dimensions (same width) or they can be of different dimensions (like becoming larger one-after-each-other). In the same way the physical dimensions of the markers can be changed, so can be their signal strength. For example: The markers are all of the same physical dimensions and they are all placed one-after-each-other with the same spacing to each other. The difference from one marker to the next is that the signal amplitude (generated by the permanently stored magnetic field, inside the marker) is increasing from one marker to the next.

Different magnetically encoded regions may be provided made of different magnetic materials, and/or may be provided with different values of magnetization. According to this embodiment, the amplitude or strength of the individual detection signals are different for

each of the magnetically encoded regions so that a unique assignment of a detection signal to one of the magnetically encoded regions, being the origin for such a signal, can be carried out.

The position sensor device according to the invention may comprise a plurality of magnetic field detectors. This further allows to refine the detection performance.

The plurality of magnetic field detectors may be arranged along the reciprocating object at constant distances from one another.

Alternatively, the plurality of magnetic field detectors may be arranged along the reciprocating object at different distances from another.

The different distances may be selected based on a linear function, a logarithmic function or a power function.

Such a mathematical function can be a positive (increasing) function or a negative (decreasing) function, meaning that the spacing can become larger from one to the next detector, or it can become smaller from one to the next.

The position sensor device according to the invention may comprise a plurality of magnetically encoded regions fixed on the reciprocating object and may comprise a plurality of magnetic field detectors.

The arrangement of the plurality of magnetically encoded regions along the reciprocating object may correspond to the arrangement of the plurality of magnetic field detectors. In other words, the arrangement of the magnetic encoded regions may be symmetrical and may thus correspond to the arrangement of the magnetic field detectors. In other words, in a reference

position of the reciprocating object, a central axis of each of the magnetic field detectors may correspond to a central axis of a corresponding one of the magnetically encoded regions.

Alternatively, at least a part of the plurality of magnetic field detectors may be arranged displaced from an arrangement of a corresponding one of the plurality of magnetically encoded regions arranged along the reciprocating object. According to this embodiment, an asymmetric configuration and arrangement of magnetic field detectors with respect to corresponding magnetically encoded regions in a reference state of the reciprocating object is achieved. For example, a first magnetically encoded region may have its central axis aligned in accordance with a central axis of a corresponding magnetic field detector. For a second magnetically encoded region, in the reference state, the central axis may be displaced with respect to a central axis of a corresponding magnetic field detector, and so on. Such a geometric offset may be used to improve the performance of the position sensor device, since the signals occur in a timely shifted manner, thus increasing the amount of detection information and allowing to refine the position determination.

The number of magnetically encoded regions may differ from the number of magnetic field detectors. For example, there may be provided three magnetically encoded regions and four magnetic field detectors. Or, two magnetic field detectors may be provided for each of the magnetically encoded regions. Or, a plurality of magnetic field detectors may be provided for each of the magnetically encoded regions, wherein the number of magnetically field detectors for any of the magnetically encoded regions may differ for different magnetically encoded regions.

In the position sensor device, the reciprocating object can be a push-pull-rod in a gearbox of a vehicle. In an automatic automotive gearbox system, the position of the various tooth-wheels (gear-wheels) may be changed by push-pull-rods. The actual position of such a rod can be measured with the position sensor device.

In the following, preferred embodiments of the position sensor array of the invention will be described. These embodiments apply also for the position sensor device, for the concrete processing apparatus and for the method of determining a position of a reciprocating object.

In the position sensor array, the reciprocating object may be a shaft. Such a shaft can be driven by an engine, and may be, for example, a hydraulically driven work cylinder of a concrete processing apparatus.

The magnetically encoding region may be provided along a part of the length of the reciprocating object. In other words, any of the magnetically encoded regions may extend along a portion of the reciprocating object in longitudinal direction, wherein another portion of the reciprocating object is free of a magnetically encoding region.

Alternatively, the magnetically encoded region may be provided along the entire length of the reciprocating object. According to this embodiment, the whole reciprocating object is magnetized.

The reciprocating object may be divided into a plurality of equally spaced segments, each segment comprising one magnetically encoded region, the magnetically encoded regions of the segments being arranged in an asymmetric manner. For instance, three segments may be provided, wherein the first segment has a magnetically encoded region in the first third of its length, the second segment has a magnetically encoded region in the middle third of its length and the third and last segment has the magnetically encoded region in the last third of its length. Such a configuration gradually increases the spacing between consecutive markers yielding a characteristic signal pattern allowing an accurate estimation of the reciprocating shaft position.

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Further, a control unit may be provided in the position sensor array adapted to control the reciprocation of the reciprocating object based on the determined position of the reciprocating object which is provided to the control unit by the position sensor device. Thus, the output of the position sensor device, namely the present position of the reciprocating object, is provided to the control unit as feedback information. Based on this back coupling, the control unit can adjust a controlling signal for controlling the reciprocation of the reciprocating object to ensure a proper operation of the reciprocating object.

In the following, preferred embodiments of the concrete processing apparatus will be described. These embodiments also apply to the position sensor device, the position sensor array and the method for determining a position of a reciprocating object.

In a concrete processing apparatus, a control unit may be provided adapted to control the reciprocation of the reciprocating shaft based on the position of the reciprocating shaft which is provided to the control unit by the position sensor device.

The concrete processing apparatus may further comprise a vehicle on which the concrete processing chamber, the reciprocating shaft and the position sensor device may be mounted. Thus, a mobile concrete processing apparatus provided on a vehicle is created which can be flexibly transported to a place of installation.

The concrete processing apparatus of the invention may further comprise a further reciprocation shaft arranged in the concrete processing chamber adapted to reciprocate to mix concrete material. The reciprocating shaft and the further reciprocating shaft are operable in a countercyclical manner. In other words, two reciprocating shafts or cylinders may be provided to mix concrete material, wherein the two reciprocating shafts move in opposite directions in each operation state. For instance, in a scenario in which the first reciprocation shaft moves in a forward direction, the second reciprocation shaft moves in the backwards

direction, and vice versa. By taking this measure, an excellent mixture of the concrete in the concrete processing apparatus is achieved. In order to accurately control the mixing of the concrete by the two reciprocating shafts, it is necessary to control the motion of the reciprocating shafts on the basis of estimated position information generated by the position sensor device. Particularly, in an operation state of the reciprocating shafts, in which they change their motion direction, it is particularly important to control the operation of the reciprocating shafts, since the energy consumption in this state is particularly high.

In the following, further aspects of the invention will be described which fall under the scope of the invention.

An amplitude, an algebraic sign, and/or a slope of a detected signal can be used to derive direction information, i.e. to determine if the reciprocating object moves from a first direction to a second direction or from the second direction to the first direction. According to the invention, one signal or a plurality of signals may be analyzed/evaluated to allow an unambiguous assignment of the detection signals to a position of the reciprocating object to be detected. The arrangement of the magnetic field detectors and of the magnetically encoded regions is preferably selected such that a signal sequence of the magnetic field detectors is unique with respect to a particular position of the reciprocating object.

The magnetic position detection principle of the invention, in contrast to optical or mechanical marker detection methods, is abrasion free and operates without errors even in a scenario in which critical conditions (like concrete powder or other kind of dirt) are present.

Further, the magnetic position detection principle of the invention can be used in a wide temperature range. The only physical restriction concerning the temperature range in which the magnetic detection principle of the invention may be implemented is the Currie temperature of the used magnetic material. Thus, the magnetic components of the system of

the invention can be used – with a reciprocating object made of industrial steel – up to 400°C and more. A limiting factor for the maximum operation temperature of the system of the invention may be the temperature up to which an isolation of a coil as a magnetic field detector keeps intact. However, with available coils, a temperature of at least 210°C can be obtained. Thus, the system of the invention is very temperature stable. Since the detection principle of the invention is contactless, a cooling element can be provided in an environment in which very high temperatures are present. Such a cooling element can be a water cooling element, for instance.

The lengths of a reciprocating shaft for an implementation in a concrete processing apparatus may be 5 meters and more.

In principle, using one magnetic field detector, for instance one coil, is sufficient. However, in order to eliminate the influence of the magnetic field of the earth, two detection coils may be used with oppositely oriented coil axis, so that the influence of the earth magnetic field can be eliminated by considering the two signals of the two coils. The detection of the position can include counting the number of markers which pass one or more magnetic field detectors per time.

The above and other aspects, objects, features and advantages of the present invention will become apparent from the following description and the appended claim, taken in conjunction with the accompanying drawings in which like parts or elements are denoted by like reference numbers.

<u>Brief Description of the Drawings</u>

The accompanying drawings, which are included to provide a further understanding of the invention and constitute a part of the specification illustrate embodiments of the invention.

In the drawings:

Fig.1 shows a position sensor array according to a first embodiment of the invention.

Fig.2 shows a position sensor array according to a second embodiment of the invention.

Fig.3 shows a position sensor array according to a third embodiment of the invention.

Fig.4 shows a position sensor array according to a forth embodiment of the invention.

Fig.5 shows a position sensor array according to a fifth embodiment of the invention.

Fig.6 shows a diagram illustrating a detection signal as detected by the magnet field detection coil of the position sensor array according to the forth embodiment of the invention.

Fig.7 shows a position sensor array according to a sixth embodiment of the invention.

Fig.8 shows a diagram illustrating a detection signal as detected by the magnet field detection coil of the position sensor array according to the sixth embodiment of the invention.

Fig.9 shows a position sensor array according to a seventh embodiment of the invention.

Fig.10 shows a concrete processing apparatus according to a first embodiment of the invention.

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Fig.11 shows a concrete processing apparatus according to a second embodiment of the invention.

Fig.12 to **Fig.67** illustrate the PCME technology which, according to the invention, is preferably used to form at least one magnetically encoding region on at least part of a reciprocating shaft.

Fig.68 and **Fig.69** show schematic views illustrating a sequence of signals captured by three magnetic field detectors generated by six magnetic encoded regions provided on a reciprocating shaft of a position sensor array according to an eighth embodiment of the invention.

Fig.70 and **Fig.71** show schematic views illustrating a sequence of signals captured by two magnetic field detectors generated by six magnetic encoded regions provided on a reciprocating shaft of a position sensor array according to a ninth embodiment of the invention.

Fig.72 shows a schematic view illustrating a sequence of signals captured by one magnetic field detector generated by six magnetic encoded regions provided on a reciprocating shaft of a position sensor array according to a tenth embodiment of the invention.

Fig.73 to **Fig.75** show hollow tubes as reciprocating objects with different embodiments for magnetic encoded regions arranged inside the hollow tube.

Fig.76, Fig.77 show a position sensor array according to an eleventh embodiment of the invention.

Detailed Description of Preferred Embodiments of the Invention

In the following, referring to **Fig.1**, a position sensor array 100 according to a first embodiment of the invention will be described.

The position sensor array 100 comprises a reciprocating shaft 101 driven by a motor (not shown in Fig.1), wherein the reciprocating shaft 101 reciprocates along a reciprocation direction 102. Further, the position sensor array 100 comprises a position sensor device for determining a position of the reciprocating shaft 101. The position sensor device for determining a position of the reciprocating shaft 101 comprises one magnetically encoded region 103 integrated in a surface region of the reciprocating shaft 101. Further, the position sensor device comprises one detection coil 104, a measuring unit 105 for measuring a magnetic field based on the electrical signals provided by the detection coil 104, and a determining unit 106. The detection coil 104 is adapted to detect a signal generated by the magnetically encoded region 103 when the magnetically encoded region 103 reciprocating with the reciprocating shaft 101 passes a surrounding area of the detection coil 104. In this surrounding area, a present magnetic element can be detected by the detection coil 104. The determining unit 106 is adapted to determine the position of the reciprocating shaft 101 based on the detected signal, which is measured by a measuring unit 105 coupled with the detection coil 104.

The magnetically encoded region 103 is realized according to the PCME technology described below. Therefore, the magnetically encoded region 103 is a permanent magnetic region having a circumferentially magnetized region of the reciprocating shaft 101 made from industrial steel. The magnetically encoded region 103 is formed by a first magnetic flow region oriented in a first direction and by a second magnetic flow region oriented in a second direction, wherein the first direction is opposite to the second direction. In a cross-sectional view of the cylindrical reciprocating shaft 101 perpendicular to the paper plane of Fig.1 and

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perpendicular to the reciprocating direction 102 of the reciprocating shaft 101, there is a first circular magnetic flow having the first direction and a first radius and the second circular magnetic flow having the second direction and a second radius, wherein the first radius is larger than the second radius.

When the reciprocating shaft 101, driven by an engine which is not shown in Fig.1, reciprocates along the reciprocation direction 102, i.e. oscillates along a direction 102 from left to right and vice versa, the magnetic flux through the detection coil 104 generated by the magnetically encoded region 103 varies with the time, since the magnetically encoded region 103 has a time dependent distance from the detection coil 104. Thus, depending on the actual position of the reciprocating shaft 101, the induced voltage in the detection coil 104 yielding a signal in the measuring unit 105, varies dependent of the actual position of the reciprocating shaft 101. Based on this measured signal, the determining unit 106 determines the actual position of the reciprocating shaft. The determining unit 106 provides this position information to the control unit 107 which uses this information to regulate control signals for controlling the reciprocation of the reciprocating shaft 101.

In the following, referring to **Fig.2**, a position sensor array 200 according to a second embodiment of the invention will be described.

In contrast to the position sensor array 100, the position sensor array 200 comprises a plurality of magnetically encoded regions divided in a first group 201 of magnetically encoded regions and a second group 202 of magnetically encoded regions which are provided at different locations on the reciprocating shaft 101. Instead of the detection coil 104, the position sensor array 200 comprises a first Hall-probe 203, a second Hall-probe 204 and third Hall-probe 205 arranged along the reciprocating shaft 101. When the reciprocating shaft 101 reciprocates along a reciprocation direction 102, the plurality of magnetically encoded regions 201, 202 pass the Hall-probes 203 to 205 to produce a significant and unique time dependent

signal pattern detected by the Hall-probes 203 to 205 and measured by the measuring unit 105, so that the determining unit 106 can calculate the position of the reciprocating shaft 101 based on the sequence of signals.

Thus, the position sensor array 200 allows to sense the actual position of the reciprocating shaft 101 on the basis of the PCME technology in cascading sequence. The PCME encoding field group 201, 202 magnetically encoded regions have a different length along the reciprocation direction 102, whereby on one side of the reciprocating shaft 101 the shorter PCME encoding region 201 is placed and at the other end of the shaft 101 is the wider PCME encoding region 202.

The reciprocating shaft 101 is a hydraulic work cylinder. As can be seen from Fig.2, the short magnetic position markers 201 are cascaded, and the long magnetic position markers 202 are cascaded.

In the following, referring to **Fig.3**, a position sensor array 300 according to a third embodiment of the invention will be described.

The position sensor array 300 differs from the position sensor array 100 in that a plurality of equal-width magnetically encoded regions 301 are provided. Each of the magnetically encoded regions 301 has an equal width, l, along the reciprocating shaft 101. The magnetically encoded regions 301 are provided at different distances from one another, namely a distances of d, 2d, and 3d. In contrast to the horizontally aligned detection coil 104 of Fig.1, Fig.3 shows a plurality of vertically aligned detection coils 302 having their coil axis arranged vertically according to the drawing of Fig.3. The different distances between adjacent magnetically encoded regions and adjacent detection coils 302 yield a time dependent pattern of signals generated in the detection coils 302 which allow to retrieve the actual position and velocity of the reciprocating shaft 101.

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The arrangement of the coils 302 with respect to the magnetically encoded regions 301 is symmetric, i.e. in a reference state of the reciprocating shaft 101 shown in Fig.3, a central axis of each of the coils 302 equals to a central axis of a corresponding one of the magnetically encoded regions 301.

In the following, referring to **Fig.4**, a position sensor array 400 according to a fourth embodiment of the invention will be described.

In the case of the position sensor array 400, a single horizontally aligned detection coil 104 is provided, and three equal-width magnetically encoded regions 301. When the shaft 101 reciprocates along direction 102, a detection signal is detected by the horizontally aligned detection coil 104 each time that one of the equal-width magnetically encoded regions 301 passes a close vicinity of the horizontally aligned detection coil 104. Thus, a sequence of signals is detected at the detection coil 104 which allows to recalculate the actual position of the shaft 101.

In the following, referring to **Fig.5**, a position sensor array 500 according to a fifth embodiment of the invention will be described.

The position sensor array 500 includes two ferromagnetic rings 501 attached on different portions of the reciprocating shaft 101. These ferromagnetic rings 501 made of iron material are separate ferromagnetic elements which are attached on the reciprocating shaft 101 to form magnetically encoded regions. Further, two horizontally aligned detection coils 104 are provided to measure a time dependent magnetic field via an induction voltage which is generated in a respective one of the coils 104 when one of the ferromagnetic rings 501 passes one of the horizontally aligned detection coils 104. As can be seen from the reference position of the reciprocating shaft 101 shown in Fig.5, the ferromagnetic rings 501 are provided at positions of the shaft 101 which are non-symmetric with respect to the detection coils 104. In

other words, in a configuration in which the position of the detection coil 104 shown on the left hand side of Fig.5 corresponds to the position of the ferromagnetic ring 501 shown on the left hand side of Fig.5, there is an offset between the position of the centre of the detecting coil 104 shown on the right hand side of Fig.5 and the position of the central axis of the ferromagnetic ring 501 shown on the right hand side of Fig.5. Consequently, the detection signals of the different coils 104 are timely shifted with respect to each other. Such a time offset yields further position information of the reciprocating shaft 101.

Referring to **Fig.6**, a diagram 600 will be described showing a signal curve 603 which can be detected by the coils 104 shown in Fig.4 when one of the magnetically encoded regions 301 passes the respective coil 104. Along an abscissa 601 of diagram 600, the position x of the reciprocating shaft 101 is shown, and along an ordinate 602, a signal amplitude A(x) is shown. Thus, the signal curve 603 allows to determine the position of the reciprocating shaft 101.

In the following, referring to **Fig.7**, a position sensor array 700 according to a sixth embodiment of the invention will be described. In contrast to the position sensor array 100, the position sensor array 700 shows an entirely magnetized shaft 701, i.e. a shaft which is entirely made of ferromagnetic material or a shaft which is magnetized along its entire length according to the PCME technology.

Fig.8 shows a diagram 800 having an abscissa 801 along which the position x of the entirely magnetized shaft 701 having a total length L is shown. Along an ordinate 802 of diagram 800, the amplitude A(x) of a signal detected by the determining unit 106 is shown. Thus, the signal of Fig.8 allows a unique identification of the actual position of the entirely magnetized shaft 701 of Fig.7.

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In the following, referring to **Fig.9**, a position sensor array 900 according to a seventh embodiment of the invention will be described.

In the case of the position sensor array 900, the reciprocating shaft 101 is divided into a plurality of equally spaced first to fourth segments 901 to 904. Each segment 901 to 904 comprises one magnetically encoded region 301, the magnetically encoded regions 301 being arranged in an asymmetric manner along the segments 901 to 904. The magnetically encoded region 301 of the first segment 901 is arranged in the very left part, the magnetically encoded region 301 of the second segment 902 is arranged in the middle-left part, the magnetically encoded region 301 of the third segment 903 is arranged in the middle-right part and the magnetically encoded region 301 of the fourth segment 904 is arranged at the very right part of the respective segment. Thus, the arrangement of the magnetically encoded regions 301 is shifted from segment to segment 901 to 904. This yields a unique signal pattern detectable by the coils 302 which allows an accurate estimation of the actual position of the shaft 101.

The equally spaced segments 901, 904 with different locations of the markers 301 allow an estimation of the position of the reciprocating shaft 101 by evaluating the signals detected by the coils 302.

In the following, referring to **Fig.10**, a concrete processing apparatus 1000 according to a first embodiment of the invention will be described.

The concrete processing apparatus 1000 is provided on a truck (not shown) equipped with a concrete mixer pump for mixing concrete material using a reciprocating shaft having the magnetic encoding of the invention. Thus, a concrete pump is equipped with a hydraulically driven work cylinder, i.e. a reciprocating shaft. In order to securely control the function of the reciprocating shaft, the position of the shaft should be known exactly. The invention provides

a method of determining the exact position of the reciprocating cylinder of the concrete processing apparatus 1000.

Fig.10 shows the concrete processing apparatus 1000 having a concrete processing chamber 1001 which includes an inlet 1003 for supplying concrete material 1005 in the concrete processing chamber 1001. A reciprocating work cylinder 1002 mixes the concrete material 1005 by reciprocating along a reciprocation direction 102 and transports the concrete material 1005 to a concrete outlet 1004 connected to a pipeline (not shown) via which the concrete is supplied to a concrete consumer.

The reciprocating work cylinder 1002 has, on its reciprocating shaft, three magnetically encoded regions 301 manufactured according to the PCME technology. Sealing elements 1007 are provided to prevent an undesired mixture of concrete material 1005 with a hydraulic fluid 1006 provided to drive the reciprocating work cylinder 1002. When the magnetically encoded regions 301 pass a detection coil 104, an induction voltage is generated in the coil 104 which is supplied to the measuring unit 105 and which allows the determining unit 106 to estimate the present position of the reciprocating work cylinder 1002. A position indicating signal, in which the actual position of the cylinder 1002 is encoded, is provided to a control unit 107 which uses the position information to optimize a driving control signal to drive the reciprocating work cylinder 1002.

Thus, the invention improves the quality of the generated concrete 1005 and the operation of the reciprocating work cylinder 1002, by enabling an improved way of driving the work cylinder 1002 based on position information of the cylinder 1002.

In the following, referring to **Fig.11**, a concrete processing apparatus 1100 according to a second embodiment of the invention will be described.

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Fig.11 shows a twin cylinder pump arrangement having a first working cylinder 1002 and a second work cylinder 1102 which allows a combination of steady and gentle pumping patterns. Hydraulic oil 1006 is pumped under pressure to the working cylinders 1002, 1102. At one time, one of the working cylinders 1002, 1102 extends, while the other one retracts at the same time. Thus, one cylinder 1002, 1102 pumps and draws in concrete material 1005, and the other cylinder 1102, 1002 pumps concrete material 1005 into a connected pipeline (not shown). The assembly of Fig.11 is mounted on a truck to form a machine which is applicable in the construction and civil engineering fields.

In contrast to the concrete processing apparatus 1000, two instead of one work cylinders 1002, 1102 are provided in the case of the concrete processing apparatus 1100, namely the reciprocating work cylinder 1002 and a further reciprocating work cylinder 1102. Moreover, a further concrete inlet 1101 for supplying concrete material in a symmetric manner is provided. Both of the reciprocating work cylinders 1002, 1102 are hydraulically driven using the hydraulic fluid 1006.

According to the operation mode shown in Fig.11, the reciprocating work cylinder 1002 moves along a first direction 1103, whereas the further reciprocating work cylinder 1102 moves along a second direction 1104 which is opposite to the first direction 1103. A separation wall 1105 separates the reciprocating work cylinders 1002, 1102 from each other. Along the shaft of each of the reciprocating cylinders 1002, 1102, a plurality of magnetic encoded regions 301 are provided which produce magnetic signals on coils 104. Each reciprocating cylinder 1002, 1102 has assigned a pair of coils 104 having opposed coil axis, so that an evaluation of the signals generated in the coils 104 of each pair of coils allow to eliminate the influence of the magnetic field of the earth to further improve the accuracy of the detected positions.

In the following, the so-called PCME ("Pulse-Current-Modulated Encoding") Sensing Technology will be described in detail, which can, according to a preferred embodiment of the invention, be implemented to form a magnetically encoded region and to detect a position information of a reciprocating object. In the following, the PCME technology will partly described in the context of torque sensing. However, according to the invention, this concept is implemented in the context of the position sensing of the invention.

In this description, there are a number of acronyms used as otherwise some explanations and descriptions may be difficult to read. While the acronyms "ASIC", "IC", and "PCB" are already market standard definitions, there are many terms that are particularly related to the magnetostriction based NCT sensing technology. It should be noted that in this description, when there is a reference to NCT technology or to PCME, it is referred to exemplary embodiments of the present invention.

Table 1 shows a list of abbreviations used in the following description of the PCME technology.

Acronym	**Description**	**Category**
ASIC	Application Specific IC	Electronics
DF	Dual Field	Primary Sensor
EMF	Earth Magnetic Field	Test Criteria
FS	Full Scale	Test Criteria
Hot-Spotting	Sensitivity to nearby Ferro magnetic material	Specification
IC	Integrated Circuit	Electronics
MFS	Magnetic Field Sensor	Sensor Component
NCT	Non Contact Torque	Technology
PCB	Printed Circuit Board	Electronics
PCME	Pulse Current Modulated Encoding	Technology

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POC	Proof-of-Concept	
RSU	Rotational Signal Uniformity	Specification
SCSP	Signal Conditioning & Signal Processing	Electronics
SF	Single Field	Primary Sensor
SH	Sensor Host	Primary Sensor
SPHC	Shaft Processing Holding Clamp	Processing Tool
SSU	Secondary Sensor Unit	Sensor Component

Table 1: List of abbreviations

The magnetic principle based mechanical-stress sensing technology allows to design and to produce a wide range of "physical-parameter-sensors" (like Force Sensing, Torque Sensing, and Material Diagnostic Analysis) that can be applied where Ferro-Magnetic materials are used. The most common technologies used to build "magnetic-principle-based" sensors are: Inductive differential displacement measurement (requires torsion shaft), measuring the changes of the materials permeability, and measuring the magnetostriction effects.

Over the last 20 years a number of different companies have developed their own and very specific solution in how to design and how to produce a magnetic principle based torque sensor (i.e. ABB, FAST, Frauenhofer Institute, FT, Kubota, MDI, NCTE, RM, Siemens, and others). These technologies are at various development stages and differ in "how-it-works", the achievable performance, the systems reliability, and the manufacturing / system cost.

Some of these technologies require that mechanical changes are made to the shaft where torque should be measured (chevrons), or rely on the mechanical torsion effect (require a long shaft that twists under torque), or that something will be attached to the shaft itself (press-fitting a ring of certain properties to the shaft surface,), or coating of the shaft surface with a

special substance. No-one has yet mastered a high-volume manufacturing process that can be applied to (almost) any shaft size, achieving tight performance tolerances, and is not based on already existing technology patents.

In the following, a magnetostriction principle based Non-Contact-Torque (NCT) Sensing Technology is described that offers to the user a whole host of new features and improved performances, previously not available. This technology enables the realization of a fully-integrated (small in space), real-time (high signal bandwidth) torque measurement, which is reliable and can be produced at an affordable cost, at any desired quantities. This technology is called: PCME (for Pulse-Current-Modulated Encoding) or Magnetostriction Transversal Torque Sensor.

The PCME technology can be applied to the shaft without making any mechanical changes to the shaft, or without attaching anything to the shaft. Most important, the PCME technology can be applied to any shaft diameter (most other technologies have here a limitation) and does not need to rotate / spin the shaft during the encoding process (very simple and low-cost manufacturing process) which makes this technology very applicable for high-volume application.

In the following, a Magnetic Field Structure (Sensor Principle) will be described.

The sensor life-time depends on a "closed-loop" magnetic field design. The PCME technology is based on two magnetic field structures, stored above each other, and running in opposite directions. When no torque stress or motion stress is applied to the shaft (also called

Sensor Host, or SH) then the SH will act magnetically neutral (no magnetic field can be sensed at the outside of the SH).

Fig.12 shows that two magnetic fields are stored in the SH and running in endless circles. The outer field runs in one direction, while the inner field runs in the opposite direction.

Fig.13 illustrates that the PCME sensing technology uses two Counter-Circular magnetic field loops that are stored on top of each other (Picky-Back mode).

When mechanical stress (like reciprocation motion or torque) is applied at both ends of the PCME magnetized SH (Sensor Host, or Shaft) then the magnetic flux lines of both magnetic structures (or loops) will tilt in proportion to the applied torque.

As illustrated in **Fig.14,** when no mechanical stresses are applied to the SH the magnetic flux lines are running in its original path. When mechanical stresses are applied the magnetic flux lines tilt in proportion to the applied stress (like linear motion or torque).

Depending on the applied torque direction (clockwise or anti-clockwise, in relation to the SH) the magnetic flux lines will either tilt to the right or tilt to the left. Where the magnetic flux lines reach the boundary of the magnetically encoded region, the magnetic flux lines from the upper layer will join-up with the magnetic flux lines from the lower layer and visa-versa. This will then form a perfectly controlled toroidal shape.

The benefits of such a magnetic structure are:

- ☐ Reduced (almost eliminated) parasitic magnetic field structures when mechanical stress is applied to the SH (this will result in better RSU performances).
- ☐ Higher Sensor-Output Signal-Slope as there are two "active" layers that compliment each other when generating a mechanical stress related signal. Explanation: When

using a single-layer sensor design, the "tilted" magnetic flux lines that exit at the encoding region boundary have to create a "return passage" from one boundary side to the other. This effort effects how much signal is available to be sensed and measured outside of the SH with the secondary sensor unit.

- ☐ There are almost no limitations on the SH (shaft) dimensions where the PCME technology will be applied to. The dual layered magnetic field structure can be adapted to any solid or hollow shaft dimensions.
- ☐ The physical dimensions and sensor performances are in a very wide range programmable and therefore can be tailored to the targeted application.
- ☐ This sensor design allows to measure mechanical stresses coming from all three dimensions axis, including in-line forces applied to the shaft (applicable as a load-cell). Explanation: Earlier magnetostriction sensor designs (for example from FAST Technology) have been limited to be sensitive in 2 dimensional axis only, and could not measure in-line forces.

Referring to **Fig.15**, when torque is applied to the SH, the magnetic flux lines from both Counter-Circular magnetic loops are connecting to each other at the sensor region boundaries.

When mechanical torque stress is applied to the SH then the magnetic field will no longer run around in circles but tilt slightly in proportion to the applied torque stress. This will cause the magnetic field lines from one layer to connect to the magnetic field lines in the other layer, and with this form a toroidal shape.

Referring to **Fig.16**, an exaggerated presentation is shown of how the magnetic flux line will form an angled toroidal structure when high levels of torque are applied to the SH.

In the following, features and benefits of the PCM-Encoding (PCME) Process will be described.

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The magnetostriction NCT sensing technology from NCTE according to the present invention offers high performance sensing features like:

- ☐ No mechanical changes required on the Sensor Host (already existing shafts can be used as they are)
- ☐ Nothing has to be attached to the Sensor Host (therefore nothing can fall off or change over the shaft-lifetime = high MTBF)
- ☐ During measurement the SH can rotate, reciprocate or move at any desired speed (no limitations on rpm)
- ☐ Very good RSU (Rotational Signal Uniformity) performances
- ☐ Excellent measurement linearity (up to 0.01% of FS)
- ☐ High measurement repeatability
- ☐ Very high signal resolution (better than 14 bit)
- ☐ Very high signal bandwidth (better than 10 kHz)

Depending on the chosen type of magnetostriction sensing technology, and the chosen physical sensor design, the mechanical power transmitting shaft (also called "Sensor Host" or in short "SH") can be used "as is" without making any mechanical changes to it or without attaching anything to the shaft. This is then called a "true" Non-Contact-Torque measurement principle allowing the shaft to rotate freely at any desired speed in both directions.

The here described PCM-Encoding (PCME) manufacturing process according to an exemplary embodiment of the present invention provides additional features no other magnetostriction technology can offer (Uniqueness of this technology):

- ☐ More then three times signal strength in comparison to alternative magnetostriction encoding processes (like the "RS" process from FAST).
- ☐ Easy and simple shaft loading process (high manufacturing through-putt).

- ☐ No moving components during magnetic encoding process (low complexity manufacturing equipment = high MTBF, and lower cost).
- ☐ Process allows NCT sensor to be "fine-tuning" to achieve target accuracy of a fraction of one percent.
- ☐ Manufacturing process allows shaft "pre-processing" and "post-processing" in the same process cycle (high manufacturing through-putt).
- ☐ Sensing technology and manufacturing process is ratio-metric and therefore is applicable to all shaft or tube diameters.
- ☐ The PCM-Encoding process can be applied while the SH is already assembled (depending on accessibility) (maintenance friendly).
- ☐ Final sensor is insensitive to axial shaft movements (the actual allowable axial shaft movement depends on the physical "length" of the magnetically encoded region).
- ☐ Magnetically encoded SH remains neutral and has little to non magnetic field when no forces (like torque) are applied to the SH.
- ☐ Sensitive to mechanical forces in all three dimensional axis.

In the following, the Magnetic Flux Distribution in the SH will be described.

The PCME processing technology is based on using electrical currents, passing through the SH (Sensor Host or Shaft) to achieve the desired, permanent magnetic encoding of the Ferro-magnetic material. To achieve the desired sensor performance and features a very specific and well controlled electrical current is required. Early experiments that used DC currents failed because of luck of understanding how small amounts and large amounts of DC electric current are travelling through a conductor (in this case the "conductor" is the mechanical power transmitting shaft, also called Sensor Host or in short "SH").

Referring to **Fig.17**, an assumed electrical current density in a conductor is illustrated.

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It is widely assumed that the electric current density in a conductor is evenly distributed over the entire cross-section of the conductor when an electric current (DC) passes through the conductor.

Referring to **Fig.18**, a small electrical current forming magnetic field that ties current path in a conductor is shown.

It is our experience that when a small amount of electrical current (DC) is passing through the conductor that the current density is highest at the centre of the conductor. The two main reasons for this are: The electric current passing through a conductor generates a magnetic field that is tying together the current path in the centre of the conductor, and the impedance is the lowest in the centre of the conductor.

Referring to **Fig.19**, a typical flow of small electrical currents in a conductor is illustrated.

In reality, however, the electric current may not flow in a "straight" line from one connection pole to the other (similar to the shape of electric lightening in the sky).

At a certain level of electric current the generated magnetic field is large enough to cause a permanent magnetization of the Ferro-magnetic shaft material. As the electric current is flowing near or at the centre of the SH, the permanently stored magnetic field will reside at the same location: near or at the centre of the SH. When now applying mechanical torque or linear force for oscillation/reciprocation to the shaft, then shaft internally stored magnetic field will respond by tilting its magnetic flux path in accordance to the applied mechanical force. As the permanently stored magnetic field lies deep below the shaft surface the measurable effects are very small, not uniform and therefore not sufficient to build a reliable NCT sensor system.

Referring to **Fig.20**, a uniform current density in a conductor at saturation level is shown.

Only at the saturation level is the electric current density (when applying DC) evenly distributed at the entire cross section of the conductor. The amount of electrical current to achieve this saturation level is extremely high and is mainly influenced by the cross section and conductivity (impedance) of the used conductor.

Referring to **Fig.21**, electric current travelling beneath or at the surface of the conductor (Skin-Effect) is shown.

It is also widely assumed that when passing through alternating current (like a radio frequency signal) through a conductor that the signal is passing through the skin layers of the conductor, called the Skin Effect. The chosen frequency of the alternating current defines the "Location / position" and "depth" of the Skin Effect. At high frequencies the electrical current will travel right at or near the surface of the conductor (A) while at lower frequencies (in the 5 to 10 Hz regions for a 20 mm diameter SH) the electrical alternating current will penetrate more the centre of the shafts cross section (E). Also, the relative current density is higher in the current occupied regions at higher AC frequencies in comparison to the relative current density near the centre of the shaft at very low AC frequencies (as there is more space available for the current to flow through).

Referring to **Fig.22**, the electrical current density of an electrical conductor (cross-section 90 deg to the current flow) when passing through the conductor an alternating current at different frequencies is illustrated.

The desired magnetic field design of the PCME sensor technology are two circular magnetic field structures, stored in two layers on top of each other ("Picky-Back"), and running in opposite direction to each other (Counter-Circular).

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Again referring to **Fig.13**, a desired magnetic sensor structure is shown: two endless magnetic loops placed on top of each other, running in opposite directions to each other: Counter-Circular "Picky-Back" Field Design.

To make this magnetic field design highly sensitive to mechanical stresses that will be applied to the SH (shaft), and to generate the largest sensor signal possible, the desired magnetic field structure has to be placed nearest to the shaft surface. Placing the circular magnetic fields to close to the centre of the SH will cause damping of the user available sensor-output-signal slope (most of the sensor signal will travel through the Ferro-magnetic shaft material as it has a much higher permeability in comparison to air), and increases the non-uniformity of the sensor signal (in relation to shaft rotation and to axial movements of the shaft in relation to the secondary sensor.

Referring to **Fig.23**, magnetic field structures stored near the shaft surface and stored near the centre of the shaft are illustrated.

It may be difficult to achieve the desired permanent magnetic encoding of the SH when using AC (alternating current) as the polarity of the created magnetic field is constantly changing and therefore may act more as a Degaussing system.

The PCME technology requires that a strong electrical current ("uni-polar" or DC, to prevent erasing of the desired magnetic field structure) is travelling right below the shaft surface (to ensure that the sensor signal will be uniform and measurable at the outside of the shaft). In addition a Counter-Circular, "picky back" magnetic field structure needs to be formed.

It is possible to place the two Counter-Circular magnetic field structures in the shaft by storing them into the shaft one after each other. First the inner layer will be stored in the SH,

and then the outer layer by using a weaker magnetic force (preventing that the inner layer will be neutralized and deleted by accident. To achieve this, the known "permanent" magnet encoding techniques can be applied as described in patents from FAST technology, or by using a combination of electrical current encoding and the "permanent" magnet encoding.

A much simpler and faster encoding process uses "only" electric current to achieve the desired Counter-Circular "Picky-Back" magnetic field structure. The most challenging part here is to generate the Counter-Circular magnetic field.

A uniform electrical current will produce a uniform magnetic field, running around the electrical conductor in a 90 deg angle, in relation to the current direction (A). When placing two conductors side-by-side (B) then the magnetic field between the two conductors seems to cancel-out the effect of each other (C). Although still present, there is no detectable (or measurable) magnetic field between the closely placed two conductors. When placing a number of electrical conductors side-by-side (D) the "measurable" magnetic field seems to go around the outside the surface of the "flat" shaped conductor.

Referring to **Fig.24**, the magnetic effects when looking at the cross-section of a conductor with a uniform current flowing through them are shown.

The "flat" or rectangle shaped conductor has now been bent into a "U"-shape. When passing an electrical current through the "U"-shaped conductor then the magnetic field following the outer dimensions of the "U"-shape is cancelling out the measurable effects in the inner halve of the "U".

Referring to **Fig.25**, the zone inside the "U"-shaped conductor seem to be magnetically "Neutral" when an electrical current is flowing through the conductor.

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When no mechanical stress is applied to the cross-section of a "U"-shaped conductor it seems that there is no magnetic field present inside of the "U" (F). But when bending or twisting the "U"-shaped conductor the magnetic field will no longer follow its original path (90 deg angle to the current flow). Depending on the applied mechanical forces, the magnetic field begins to change slightly its path. At that time the magnetic-field-vector that is caused by the mechanical stress can be sensed and measured at the surface of the conductor, inside and outside of the "U"-shape. Note: This phenomena is applies only at very specific electrical current levels.

The same applies to the "O"-shaped conductor design. When passing a uniform electrical current through an "O"-shaped conductor (Tube) the measurable magnetic effects inside of the "O" (Tube) have cancelled-out each other (G).

Referring to **Fig.26**, the zone inside the "O"-shaped conductor seem to be magnetically "Neutral" when an electrical current is flowing through the conductor.

However, when mechanical stresses are applied to the "O"-shaped conductor (Tube) it becomes evident that there has been a magnetic field present at the inner side of the "O"-shaped conductor. The inner, counter directional magnetic field (as well as the outer magnetic field) begins to tilt in relation to the applied torque stresses. This tilting field can be clearly sensed and measured.

In the following, an Encoding Pulse Design will be described.

To achieve the desired magnetic field structure (Counter-Circular, Picky-Back, Fields Design) inside the SH, according to an exemplary embodiment of a method of the present invention, unipolar electrical current pulses are passed through the Shaft (or SH). By using "pulses" the desired "Skin-Effect" can be achieved. By using a "unipolar" current direction (not changing

the direction of the electrical current) the generated magnetic effect will not be erased accidentally.

The used current pulse shape is most critical to achieve the desired PCME sensor design. Each parameter has to be accurately and repeatable controlled: Current raising time, Constant current on-time, Maximal current amplitude, and Current falling time. In addition it is very critical that the current enters and exits very uniformly around the entire shaft surface.

In the following, a Rectangle Current Pulse Shape will be described.

Referring to **Fig.27**, a rectangle shaped electrical current pulse is illustrated.

A rectangle shaped current pulse has a fast raising positive edge and a fast falling current edge. When passing a rectangle shaped current pulse through the SH, the raising edge is responsible for forming the targeted magnetic structure of the PCME sensor while the flat "on" time and the falling edge of the rectangle shaped current pulse are counter productive.

Referring to **Fig.28**, a relationship between rectangles shaped Current Encoding Pulse-Width (Constant Current On-Time) and Sensor Output Signal Slope is shown.

In the following example a rectangle shaped current pulse has been used to generate and store the Couter-Circilar "Picky-Back" field in a 15 mm diameter, 14CrNi14 shaft. The pulsed electric current had its maximum at around 270 Ampere. The pulse "on-time" has been electronically controlled. Because of the high frequency component in the rising and falling edge of the encoding pulse, this experiment can not truly represent the effects of a true DC encoding SH. Therefore the Sensor-Output-Signal Slope-curve eventually flattens-out at above 20 mV/Nm when passing the Constant-Current On-Time of 1000 ms.

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Without using a fast raising current-pulse edge (like using a controlled ramping slope) the sensor output signal slope would have been very poor (below 10 mV/Nm). Note: In this experiment (using 14CrNi14) the signal hysteresis was around 0.95% of the FS signal (FS = 75 Nm torque).

Referring to **Fig.29**, increasing the Sensor-Output Signal-Slope by using several rectangle shaped current pulses in succession is shown.

The Sensor-Output-Signal slope can be improved when using several rectangle shaped current-encoding-pulses in successions. In comparisons to other encoding-pulse-shapes the fast falling current-pulse signal slope of the rectangle shaped current pulse will prevent that the Sensor-Output-Signal slope may ever reach an optimal performance level. Meaning that after only a few current pulses (2 to 10) have been applied to the SH (or Shaft) the Sensor-Output Signal-Slope will no longer rise.

In the following, a Discharge Current Pulse Shape is described.

The Discharge-Current-Pulse has no Constant-Current ON-Time and has no fast falling edge. Therefore the primary and most felt effect in the magnetic encoding of the SH is the fast raising edge of this current pulse type.

As shown in **Fig.30**, a sharp raising current edge and a typical discharging curve provides best results when creating a PCME sensor.

Referring to **Fig.31**, a PCME Sensor-Output Signal-Slope optimization by identifying the right pulse current is illustrated.

At the very low end of the pulse current scale (0 to 75 A for a 15 mm diameter shaft, 14CrNi14 shaft material) the "Discharge-Current-Pulse type is not powerful enough to cross the magnetic threshold needed to create a lasting magnetic field inside the Ferro magnetic shaft. When increasing the pulse current amplitude the double circular magnetic field structure begins to form below the shaft surface. As the pulse current amplitude increases so does the achievable torque sensor-output signal-amplitude of the secondary sensor system. At around 400A to 425A the optimal PCME sensor design has been achieved (the two counter flowing magnetic regions have reached their most optimal distance to each other and the correct flux density for best sensor performances.

Referring to **Fig.32**, Sensor Host (SH) cross section with the optimal PCME electrical current density and location during the encoding pulse is illustrated.

When increasing further the pulse current amplitude the absolute, torque force related, sensor signal amplitude will further increase (curve 2) for some time while the overall PCME-typical sensor performances will decrease (curve 1). When passing 900A Pulse Current Amplitude (for a 15 mm diameter shaft) the absolute, torque force related, sensor signal amplitude will begin to drop as well (curve 2) while the PCME sensor performances are now very poor (curve 1).

Referring to **Fig.33**, Sensor Host (SH) cross sections and the electrical pulse current density at different and increasing pulse current levels is shown.

As the electrical current occupies a larger cross section in the SH the spacing between the inner circular region and the outer (near the shaft surface) circular region becomes larger.

Referring to **Fig.34**, better PCME sensor performances will be achieved when the spacing between the Counter-Circular "Picky-Back" Field design is narrow (A).

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The desired double, counter flow, circular magnetic field structure will be less able to create a close loop structure under torque forces which results in a decreasing secondary sensor signal amplitude.

Referring to **Fig.35**, flattening-out the current-discharge curve will also increase the Sensor-Output Signal-Slope.

When increasing the Current-Pulse discharge time (making the current pulse wider) (B) the Sensor-Output Signal-Slope will increase. However the required amount of current is very high to reduce the slope of the falling edge of the current pulse. It might be more practical to use a combination of a high current amplitude (with the optimal value) and the slowest possible discharge time to achieve the highest possible Sensor-Output Signal Slope.

In the following, Electrical Connection Devices in the frame of Primary Sensor Processing will be described.

The PCME technology (it has to be noted that the term 'PCME' technology is used to refer to exemplary embodiments of the present invention) relies on passing through the shaft very high amounts of pulse-modulated electrical current at the location where the Primary Sensor should be produced. When the surface of the shaft is very clean and highly conductive a multi-point Cupper or Gold connection may be sufficient to achieve the desired sensor signal uniformity. Important is that the Impedance is identical of each connection point to the shaft surface. This can be best achieved when assuring the cable length (L) is identical before it joins the main current connection point (I).

Referring to **Fig.36**, a simple electrical multi-point connection to the shaft surface is illustrated.

However, in most cases a reliable and repeatable multi-point electrical connection can be only achieved by ensuring that the impedance at each connection point is identical and constant. Using a spring pushed, sharpened connector will penetrate possible oxidation or isolation layers (maybe caused by finger prints) at the shaft surface.

Referring to **Fig.37**, a multi channel, electrical connecting fixture, with spring loaded contact points is illustrated.

When processing the shaft it is most important that the electrical current is injected and extracted from the shaft in the most uniform way possible. The above drawing shows several electrical, from each other insulated, connectors that are held by a fixture around the shaft. This device is called a Shaft-Processing-Holding-Clamp (or SPHC). The number of electrical connectors required in a SPHC depends on the shafts outer diameter. The larger the outer diameter, the more connectors are required. The spacing between the electrical conductors has to be identical from one connecting point to the next connecting point. This method is called Symmetrical-"Spot"-Contacts.

Referring to **Fig.38**, it is illustrated that increasing the number of electrical connection points will assist the efforts of entering and exiting the Pulse-Modulated electrical current. It will also increase the complexity of the required electronic control system.

Referring to **Fig.39**, an example of how to open the SPHC for easy shaft loading is shown.

In the following, an encoding scheme in the frame of Primary Sensor Processing will be described.

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The encoding of the primary shaft can be done by using permanent magnets applied at a rotating shaft or using electric currents passing through the desired section of the shaft. When using permanent magnets a very complex, sequential procedure is necessary to put the two layers of closed loop magnetic fields, on top of each other, in the shaft. When using the PCME procedure the electric current has to enter the shaft and exit the shaft in the most symmetrical way possible to achieve the desired performances.

Referring to **Fig.40**, two SPHCs (Shaft Processing Holding Clamps) are placed at the borders of the planned sensing encoding region. Through one SPHC the pulsed electrical current (I) will enter the shaft, while at the second SPHC the pulsed electrical current (I) will exit the shaft. The region between the two SPHCs will then turn into the primary sensor.

This particular sensor process will produce a Single Field (SF) encoded region. One benefit of this design (in comparison to those that are described below) is that this design is insensitive to any axial shaft movements in relation to the location of the secondary sensor devices. The disadvantage of this design is that when using axial (or in-line) placed MFS coils the system will be sensitive to magnetic stray fields (like the earth magnetic field).

Referring to **Fig.41**, a Dual Field (DF) encoded region (meaning two independent functioning sensor regions with opposite polarity, side-by-side) allows cancelling the effects of uniform magnetic stray fields when using axial (or in-line) placed MFS coils. However, this primary sensor design also shortens the tolerable range of shaft movement in axial direction (in relation to the location of the MFS coils). There are two ways to produce a Dual Field (DF) encoded region with the PCME technology. The sequential process, where the magnetic encoded sections are produced one after each other, and the parallel process, where both magnetic encoded sections are produced at the same time.

The first process step of the sequential dual field design is to magnetically encode one sensor section (identically to the Single Field procedure), whereby the spacing between the two SPHC has to be halve of the desired final length of the Primary Sensor region. To simplify the explanations of this process we call the SPHC that is placed in the centre of the final Primary Sensor Region the Centre SPHC (C-SPHC), and the SPHC that is located at the left side of the Centre SPHC: L-SPHC.

Referring to **Fig.42**, the second process step of the sequential Dual Field encoding will use the SPHC that is located in the centre of the Primary Sensor region (called C-SPHC) and a second SPHC that is placed at the other side (the right side) of the centre SPHC, called R-SPHC. Important is that the current flow direction in the centre SPHC (C-SPHC) is identical at both process steps.

Referring to **Fig.43**, the performance of the final Primary Sensor Region depends on how close the two encoded regions can be placed in relation to each other. And this is dependent on the design of the used centre SPHC. The narrower the in-line space contact dimensions are of the C-SPHC, the better are the performances of the Dual Field PCME sensor.

Fig.44 shows the pulse application according to another exemplary embodiment of the present invention. As my be taken from the above drawing, the pulse is applied to three locations of the shaft. Due to the current distribution to both sides of the middle electrode where the current I is entered into the shaft, the current leaving the shaft at the lateral electrodes is only half the current entered at the middle electrode, namely ½ I. The electrodes are depicted as rings which dimensions are adapted to the dimensions of the outer surface of the shaft. However, it has to be noted that other electrodes may be used, such as the electrodes comprising a plurality of pin electrodes described later in this text.

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Referring to **Fig.45**, magnetic flux directions of the two sensor sections of a Dual Field PCME sensor design are shown when no torque or linear motion stress is applied to the shaft. The counter flow magnetic flux loops do not interact with each other.

Referring to **Fig.46**, when torque forces or linear stress forces are applied in a particular direction then the magnetic flux loops begin to run with an increasing tilting angle inside the shaft. When the tilted magnetic flux reaches the PCME segment boundary then the flux line interacts with the counterflowing magnetic flux lines, as shown.

Referring to **Fig.47**, when the applied torque direction is changing (for example from clock-wise to counter-clock-wise) so will change the tilting angle of the counterflow magnetic flux structures inside the PCM Encoded shaft.

In the following, a Multi Channel Current Driver for Shaft Processing will be described.

In cases where an absolute identical impedance of the current path to the shaft surface can not be guaranteed, then electric current controlled driver stages can be used to overcome this problem.

Referring to **Fig.48**, a six-channel synchronized Pulse current driver system for small diameter Sensor Hosts (SH) is shown. As the shaft diameter increases so will the number of current driver channels.

In the following, Bras Ring Contacts and Symmetrical "Spot" Contacts will be described.

When the shaft diameter is relative small and the shaft surface is clean and free from any oxidations at the desired Sensing Region, then a simple "Bras"-ring (or Copper-ring) contact method can be chosen to process the Primary Sensor.

Referring to **Fig.49**, bras-rings (or Copper-rings) tightly fitted to the shaft surface may be used, with solder connections for the electrical wires. The area between the two Bras-rings (Copper-rings) is the encoded region.

However, it is very likely that the achievable RSU performances are much lower then when using the Symmetrical "Spot" Contact method.

In the following, a Hot-Spotting concept will be described.

A standard single field (SF) PCME sensor has very poor Hot-Spotting performances. The external magnetic flux profile of the SF PCME sensor segment (when torque is applied) is very sensitive to possible changes (in relation to Ferro magnetic material) in the nearby environment. As the magnetic boundaries of the SF encoded sensor segment are not well defined (not "Pinned Down") they can "extend" towards the direction where Ferro magnet material is placed near the PCME sensing region.

Referring to **Fig.50**, a PCME process magnetized sensing region is very sensitive to Ferro magnetic materials that may come close to the boundaries of the sensing regions.

To reduce the Hot-Spotting sensor sensitivity the PCME sensor segment boundaries have to be better defined by pinning them down (they can no longer move).

Referring to **Fig.51**, a PCME processed Sensing region with two "Pinning Field Regions" is shown, one on each side of the Sensing Region.

By placing Pinning Regions closely on either side the Sensing Region, the Sensing Region Boundary has been pinned down to a very specific location. When Ferro magnetic material is

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coming close to the Sensing Region, it may have an effect on the outer boundaries of the Pinning Regions, but it will have very limited effects on the Sensing Region Boundaries.

There are a number of different ways, according to exemplary embodiments of the present invention how the SH (Sensor Host) can be processed to get a Single Field (SF) Sensing Region and two Pinning Regions, one on each side of the Sensing Region. Either each region is processed after each other (Sequential Processing) or two or three regions are processed simultaneously (Parallel Processing). The Parallel Processing provides a more uniform sensor (reduced parasitic fields) but requires much higher levels of electrical current to get to the targeted sensor signal slope.

Referring to **Fig.52**, a parallel processing example for a Single Field (SF) PCME sensor with Pinning Regions on either side of the main sensing region is illustrated, in order to reduce (or even eliminate) Hot-Spotting.

A Dual Field PCME Sensor is less sensitive to the effects of Hot-Spotting as the sensor centre region is already Pinned-Down. However, the remaining Hot-Spotting sensitivity can be further reduced by placing Pinning Regions on either side of the Dual-Field Sensor Region.

Referring to **Fig.53**, a Dual Field (DF) PCME sensor with Pinning Regions either side is shown.

When Pinning Regions are not allowed or possible (example: limited axial spacing available) then the Sensing Region has to be magnetically shielded from the influences of external Ferro Magnetic Materials.

In the following, the Rotational Signal Uniformity (RSU) will be explained.

The RSU sensor performance are, according to current understanding, mainly depending on how circumferentially uniform the electrical current entered and exited the SH surface, and the physical space between the electrical current entry and exit points. The larger the spacing between the current entry and exit points, the better is the RSU performance.

Referring to **Fig.54**, when the spacings between the individual circumferential placed current entry points are relatively large in relation to the shaft diameter (and equally large are the spacings between the circumferentially placed current exit points) then this will result in very poor RSU performances. In such a case the length of the PCM Encoding Segment has to be as large as possible as otherwise the created magnetic field will be circumferentially non-uniform.

Referring to **Fig.55**, by widening the PCM Encoding Segment the circumferentially magnetic field distribution will become more uniform (and eventually almost perfect) at the halve distance between the current entry and current exit points. Therefore the RSU performance of the PCME sensor is best at the halve way-point between of the current-entry / current-exit points.

Next, the basic design issues of a NCT sensor system will be described.

Without going into the specific details of the PCM-Encoding technology, the end-user of this sensing technology need to now some design details that will allow him to apply and to use this sensing concept in his application. The following pages describe the basic elements of a magnetostriction based NCT sensor (like the primary sensor, secondary sensor, and the SCSP

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electronics), what the individual components look like, and what choices need to be made when integrating this technology into an already existing product.

In principle the PCME sensing technology can be used to produce a stand-alone sensor product. However, in already existing industrial applications there is little to none space available for a "stand-alone" product. The PCME technology can be applied in an existing product without the need of redesigning the final product.

In case a stand-alone torque sensor device or position detecting sensor device will be applied to a motor-transmission system it may require that the entire system need to undergo a major design change.

In the following, referring to Fig.56, a possible location of a PCME sensor at the shaft of an engine is illustrated.

Next, Sensor Components will be explained.

A non-contact magnetostriction sensor (NCT-Sensor), as shown in **Fig.57**, may consist, according to an exemplary embodiment of the present invention, of three main functional elements: The Primary Sensor, the Secondary Sensor, and the Signal Conditioning & Signal Processing (SCSP) electronics.

Depending on the application type (volume and quality demands, targeted manufacturing cost, manufacturing process flow) the customer can chose to purchase either the individual components to build the sensor system under his own management, or can subcontract the production of the individual modules.

Fig.58 shows a schematic illustration of components of a non-contact torque sensing device. However, these components can also be implemented in a non-contact position sensing device.

In cases where the annual production target is in the thousands of units it may be more efficient to integrate the "primary-sensor magnetic-encoding-process" into the customers manufacturing process. In such a case the customer needs to purchase application specific "magnetic encoding equipment".

In high volume applications, where cost and the integrity of the manufacturing process are critical, it is typical that NCTE supplies only the individual basic components and equipment necessary to build a non-contact sensor:

- ☐ ICs (surface mount packaged, Application-Specific Electronic Circuits)
- ☐ MFS-Coils (as part of the Secondary Sensor)
- ☐ Sensor Host Encoding Equipment (to apply the magnetic encoding on the shaft = Primary Sensor)

Depending on the required volume, the MFS-Coils can be supplied already assembled on a frame, and if desired, electrically attached to a wire harness with connector. Equally the SCSP (Signal Conditioning & Signal Processing) electronics can be supplied fully functional in PCB format, with or without the MFS-Coils embedded in the PCB.

Fig.59 shows components of a sensing device.

As can be seen from **Fig.60**, the number of required MFS-coils is dependent on the expected sensor performance and the mechanical tolerances of the physical sensor design. In a well designed sensor system with perfect Sensor Host (SH or magnetically encoded shaft) and

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minimal interferences from unwanted magnetic stray fields, only 2 MFS-coils are needed. However, if the SH is moving radial or axial in relation to the secondary sensor position by more than a few tenths of a millimeter, then the number of MFS-coils need to be increased to achieve the desired sensor performance.

In the following, a control and/or evaluation circuitry will be explained.

The SCSP electronics, according to an exemplary embodiment of the present invention, consist of the NCTE specific ICs, a number of external passive and active electronic circuits, the printed circuit board (PCB), and the SCSP housing or casing. Depending on the environment where the SCSP unit will be used the casing has to be sealed appropriately.

Depending on the application specific requirements NCTE (according to an exemplary embodiment of the present invention) offers a number of different application specific circuits:

- ☐ Basic Circuit
- ☐ Basic Circuit with integrated Voltage Regulator
- ☐ High Signal Bandwidth Circuit
- ☐ Optional High Voltage and Short Circuit Protection Device
- ☐ Optional Fault Detection Circuit

Fig.61 shows a single channel, low cost sensor electronics solution.

Fig.62 shows a dual channel, short circuit protected system design with integrated fault detection. This design consists of 5 ASIC devices and provides a high degree of system safety. The Fault-Detection IC identifies when there is a wire breakage anywhere in the

sensor system, a fault with the MFS coils, or a fault in the electronic driver stages of the "Basic IC".

Next, the Secondary Sensor Unit will be explained.

The Secondary Sensor may, according to one embodiment shown in **Fig.63**, consist of the elements: One to eight MFS (Magnetic Field Sensor) Coils, the Alignment- & Connection-Plate, the wire harness with connector, and the Secondary-Sensor-Housing.

The MFS-coils may be mounted onto the Alignment-Plate. Usually the Alignment-Plate allows that the two connection wires of each MFS-Coil are soldered / connected in the appropriate way. The wire harness is connected to the alignment plate. This, completely assembled with the MFS-Coils and wire harness, is then embedded or held by the Secondary-Sensor-Housing.

The main element of the MFS-Coil is the core wire, which has to be made out of an amorphous-like material.

Depending on the environment where the Secondary-Sensor-Unit will be used, the assembled Alignment Plate has to be covered by protective material. This material can not cause mechanical stress or pressure on the MFS-coils when the ambient temperature is changing.

In applications where the operating temperature will not exceed +110 deg C the customer has the option to place the SCSP electronics (ASIC) inside the secondary sensor unit (SSU). While the ASIC devices can operated at temperatures above +125 deg C it will become increasingly more difficult to compensate the temperature related signal-offset and signal-gain changes.

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The recommended maximal cable length between the MFS-coils and the SCSP electronics is 2 meters. When using the appropriate connecting cable, distances of up to 10 meters are achievable. To avoid signal-cross-talk in multi-channel applications (two independent SSUs operating at the same Primary Sensor location = Redundant Sensor Function), specially shielded cable between the SSUs and the SCSP Electronics should be considered.

When planning to produce the Secondary-Sensor-Unit (SSU) the producer has to decide which part / parts of the SSU have to be purchased through subcontracting and which manufacturing steps will be made in-house.

In the following, Secondary Sensor Unit Manufacturing Options will be described.

When integrating the NCT-Sensor into a customized tool or standard transmission system then the systems manufacturer has several options to choose from:

- ☐ custom made SSU (including the wire harness and connector)
- ☐ selected modules or components; the final SSU assembly and system test may be done under the customer's management.
- ☐ only the essential components (MFS-coils or MFS-core-wire, Application specific ICs) and will produce the SSU in-house.

Fig.64 illustrates an exemplary embodiment of a Secondary Sensor Unit Assembly.

Next, a Primary Sensor Design is explained.

The SSU (Secondary Sensor Units) can be placed outside the magnetically encoded SH (Sensor Host) or, in case the SH is hollow, inside the SH. The achievable sensor signal

amplitude is of equal strength but has a much better signal-to-noise performance when placed inside the hollow shaft.

Fig.65 illustrates two configurations of the geometrical arrangement of Primary Sensor and Secondary Sensor.

Improved sensor performances may be achieved when the magnetic encoding process is applied to a straight and parallel section of the SH (shaft). For a shaft with 15 mm to 25 mm diameter the optimal minimum length of the Magnetically Encoded Region is 25 mm. The sensor performances will further improve if the region can be made as long as 45 mm (adding Guard Regions). In complex and highly integrated transmission (gearbox) systems it will be difficult to find such space. Under more ideal circumstances, the Magnetically Encoding Region can be as short as 14 mm, but this bears the risk that not all of the desired sensor performances can be achieved.

As illustrated in **Fig.66**, the spacing between the SSU (Secondary Sensor Unit) and the Sensor Host surface, according to an exemplary embodiment of the present invention, should be held as small as possible to achieve the best possible signal quality.

Next, the Primary Sensor Encoding Equipment will be described.

An example is shown in **Fig.67**.

Depending on which magnetostriction sensing technology will be chosen, the Sensor Host (SH) needs to be processed and treated accordingly. The technologies vary by a great deal from each other (ABB, FAST, FT, Kubota, MDI, NCTE, RM, Siemens, ...) and so does the processing equipment required. Some of the available magnetostriction sensing technologies

do not need any physical changes to be made on the SH and rely only on magnetic processing (MDI, FAST, NCTE).

While the MDI technology is a two phase process, the FAST technology is a three phase process, and the NCTE technology a one phase process, called PCM Encoding.

One should be aware that after the magnetic processing, the Sensor Host (SH or Shaft), has become a "precision measurement" device and has to be treated accordingly. The magnetic processing should be the very last step before the treated SH is carefully placed in its final location.

The magnetic processing should be an integral part of the customer's production process (in-house magnetic processing) under the following circumstances:

- ☐ High production quantities (like in the thousands)
- ☐ Heavy or difficult to handle SH (e.g. high shipping costs)
- ☐ Very specific quality and inspection demands (e.g. defense applications)

In all other cases it may be more cost effective to get the SH magnetically treated by a qualified and authorized subcontractor, such as NCTE. For the "in-house" magnetic processing dedicated manufacturing equipment is required. Such equipment can be operated fully manually, semi-automated, and fully automated. Depending on the complexity and automation level the equipment can cost anywhere from EUR 20k to above EUR 500k.

In the following, further embodiments of the invention will be described which may or may not be realized with PCME technology.

Fig.68 and **Fig.69** show schematic views illustrating a sequence of signals 6810 captured by three magnetic field detectors 6800, 6801, 6802 generated by six magnetic encoded regions (see "1" to "6") provided with (from left to right) increasing distances from one another on a reciprocating shaft (not shown) of a position sensor array according to an eighth embodiment of the invention. A first pickup location 6820 and a second pickup location 6830 are shown. The six magnetic encoded regions (markers) have the same physical dimension (width of the markers is constant), but the location in relation to each other is changing.

As can be seen from Fig.69, when using three pickup modules 6800, 6801, 6802, then the usable axial-measurement range is much larger than in a scenario of using one or two pickup modules, since there are no "dead" areas (at least two pickup devices have a usable signal at any given location, at any point of time).

Fig.70 and **Fig.71** show schematic views illustrating a sequence of signals 7000 captured by two magnetic field detectors 6800, 6801 generated by six magnetic encoded regions (see "1" to "6") provided with (from left to right) increasing distances from one another provided on a reciprocating shaft (not shown) of a position sensor array according to a ninth embodiment of the invention.

When using two pickup devices 6800, 6801, the axial measurement range expands considerably than when using only one pickup device. However, there are still "dead" areas 7100 between the markers where there is no sufficient information available through the pickup system. Apart from the "dead" areas 7100, the axial position can be determined accurately. Two pickups enable to determine accurately the axial position when two signals are present at any given location.

Fig.72 shows a schematic view illustrating a sequence of signals 6810 captured by one magnetic field detector 6800 generated by six magnetic encoded regions (see "1" to "6")

provided with (from left to right) increasing distances from one another provided on a reciprocating shaft (not shown) of a position sensor array according to a tenth embodiment of the invention. This embodiment allows to obtain axial position information with low effort.

Fig.73 to Fig.75 show a hollow tube 7300 as reciprocating object with different embodiments for magnetic encoded regions arranged inside the hollow tube. The magnetic field generated inside the tube 7300 has to be strong enough to penetrate the outer tube wall.

According to the embodiment shown in **Fig.73**, a permanent magnet 7301 (synthetic magnet) is placed inside the tube.

According to the embodiment shown in **Fig.74**, a coil 7400 (inductor) is placed inside the tube which can be magnetized by an electrical power source 7401.

According to the embodiment shown in **Fig.75**, a helical coil 7500 is placed inside the tube which can be magnetized by an electrical power source 7401.

Fig.76, Fig.77 show a position sensor array 7600 according to an eleventh embodiment of the invention.

In an automatic automotive gearbox system, as shown in Fig.76, Fig.77, the position of the various tooth-wheels (gear-wheels) are changed by push-pull-rods 7601. In a passenger car gearbox system may be particularly four or more push-pull-rods 7601 to control the gear positions of the cars transmission system. The push-pull-rods 7601 may be operated by an electric or pneumatic or hydraulic actuator. The actuators operate a hook 7602 which is inserted into a hole from the push-pull-rod 7601.

The push-pull-rod may 7601 move as little as +/-10 mm (passenger car gearbox) or much more (truck gearbox). The optimal operation of the gearbox requires that the push-pull-rods 7601 are moved to precise positions with little tolerances.

As the axial measurement range is relatively short (+/-10mm, up to +/-20mm) only one magnetic marker 103 is required for measuring the position of the push-pull-rod 7601. The magnetic marker 103 can be placed at any desired location of the push-pull-rod 7601 whereby the cross-section of the push-pull-rod 7601 where the marker 103 will be placed can be round, square, rectangle, or any other desired shape. As the push-pull-rod 7601 does not rotate, a non-uniform (non-round) shape of the rod's cross section is acceptable.

Fig.76 shows a typical gearbox push-pull-rod 7601 design, required to change the gear (tooth-wheel) position inside the gearbox by means of an externally placed actuator. The actuator is attached to the hook 7602 which is attached to the end of the push-pull-rod 7601.

Fig.77 shows a detailed view of the push-pull-rod 7601 with an magnetic marker encoding 103 and at least one magnetic field detecting device 104. The magnetic field detecting device 104 (example: coil) will detect the exact axial (linear) position of the push-pull-rod 7601 in relation to the position of the magnetic field detecting device 104.

It should be noted that the term "comprising" does not exclude other elements or steps and the "a" or "an" does not exclude a plurality. Also elements described in association with different embodiments may be combined.

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What Is claimed is:

A position sensor device for determining a position of a reciprocating object, comprising

at least one magnetically encoded region fixed on a reciprocating object;

at least one magnetic field detector;

a position determining unit;

wherein the magnetic field detector is adapted to detect a signal generated by the magnetically encoded region when the magnetically encoded region reciprocating with the reciprocating object passes a surrounding area of the magnetic field detector;

wherein the position determining unit is adapted to determine the position of a reciprocating object based on the detected signal;

wherein the at least one magnetically encoded region is formed by a first magnetic flow region oriented in a first direction and by a second magnetic flow region oriented in a second direction, wherein the first direction is opposite to the second direction;

wherein in a cross-sectional view of the reciprocating object, there is the first circular magnetic flow having the first direction and a first radius and the second circular magnetic flow having the second direction and a second radius, wherein the first radius is larger than the second radius.

Abstract

A position sensor device, a position sensor array, a concrete processing apparatus and a method for determining a position of a reciprocating object

A position sensor device for determining a position of a reciprocating object, comprising at least one magnetically encoded region fixed on a reciprocating object, comprising at least one magnetic field detector, and comprising a position determining unit. The magnetic field detector is adapted to detect a signal generated by the magnetically encoded region when the magnetically encoded region reciprocating with the reciprocating object passes a surrounding area of the magnetically encoded region. The position determining unit is adapted to determine a position of a reciprocating object based on the detected magnetic signal.

(Fig.10)

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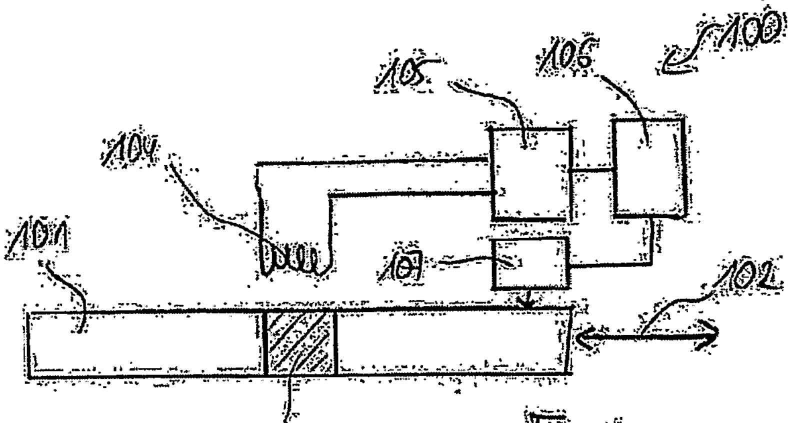


Fig 1

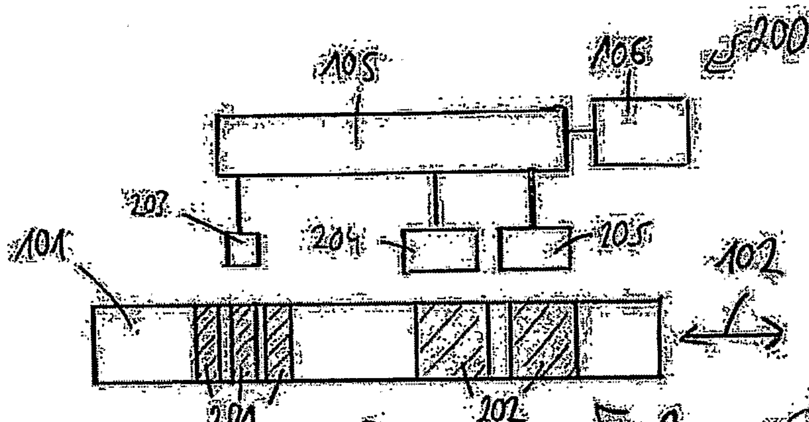


Fig 2

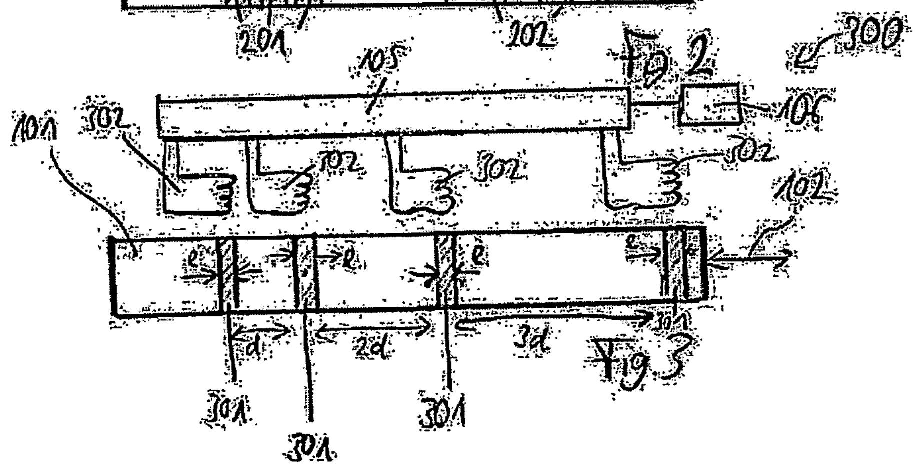


Fig 3

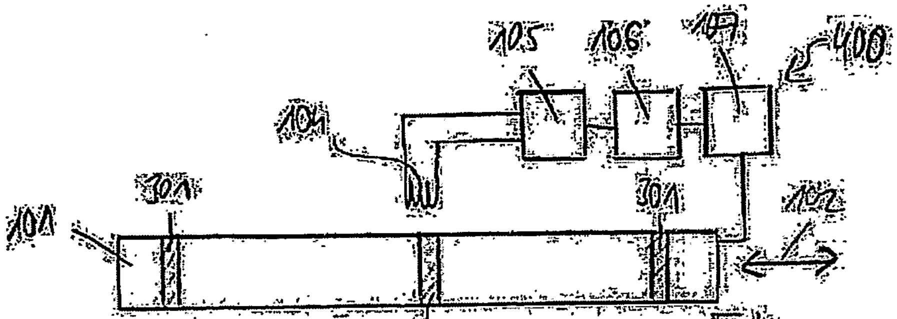


Fig 4

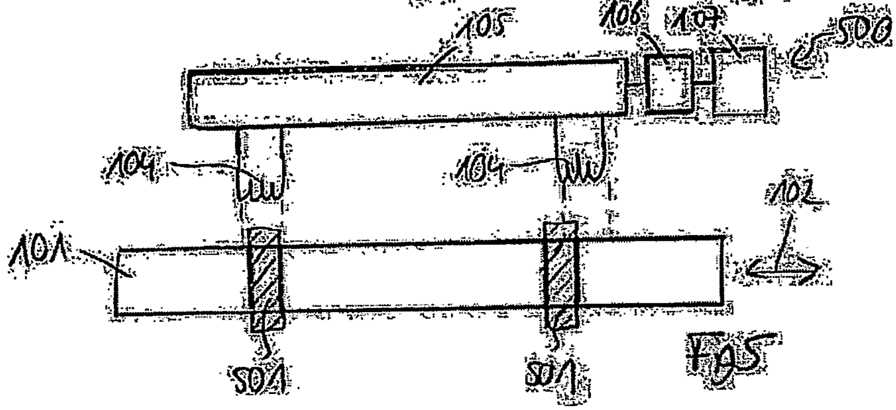


Fig 5

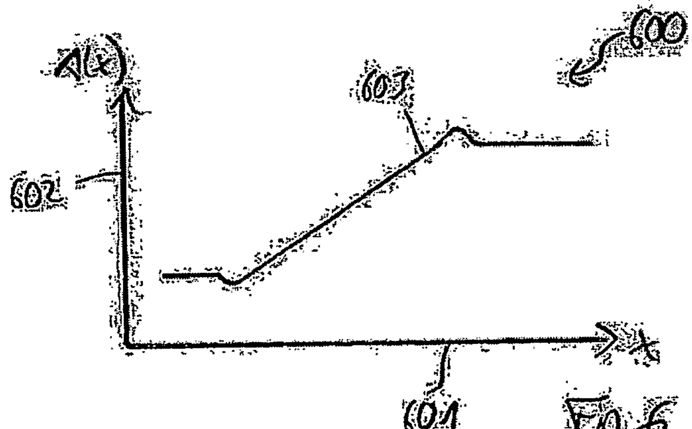


Fig 6

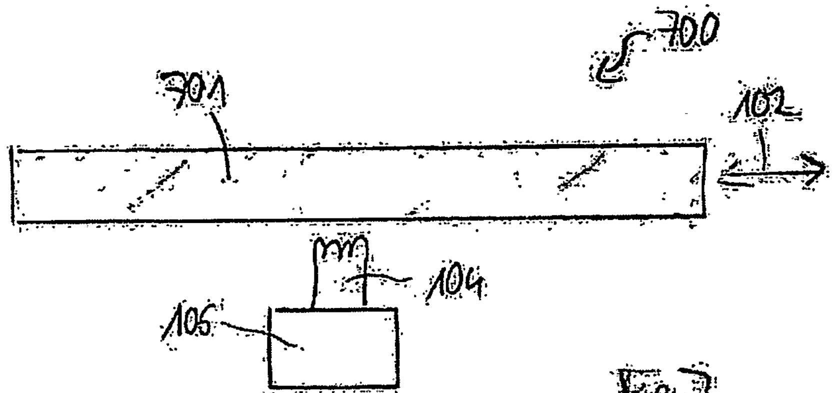


Fig 7

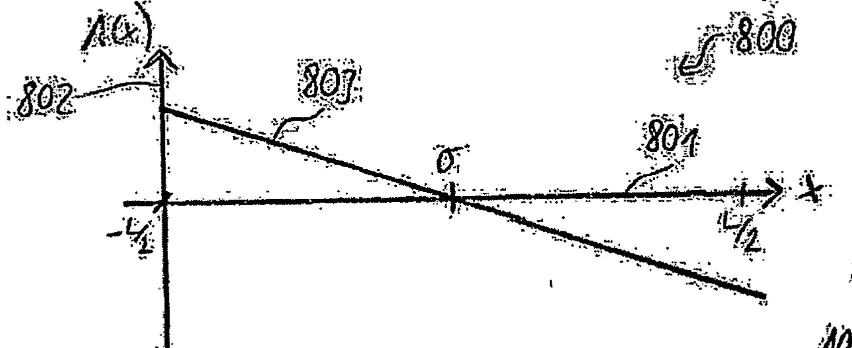


Fig. 8

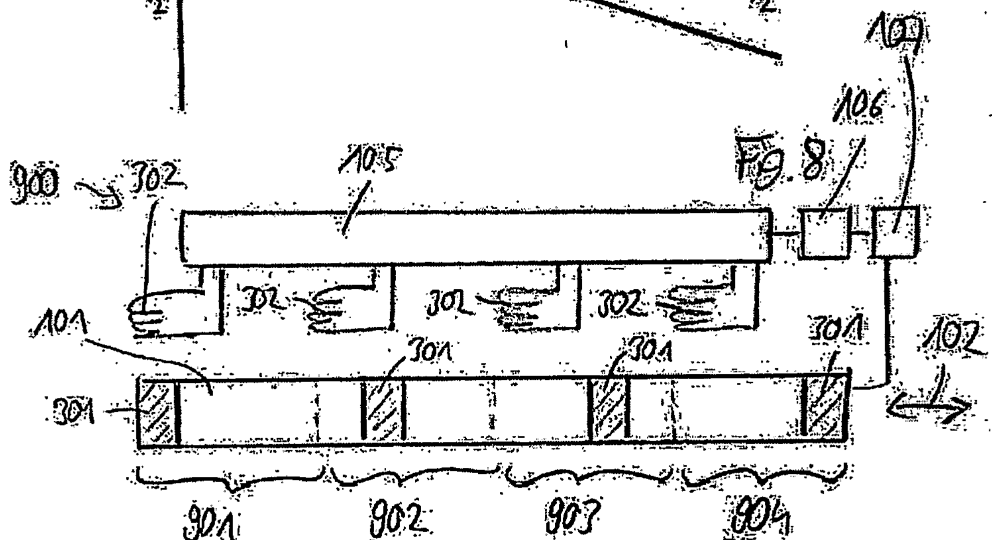
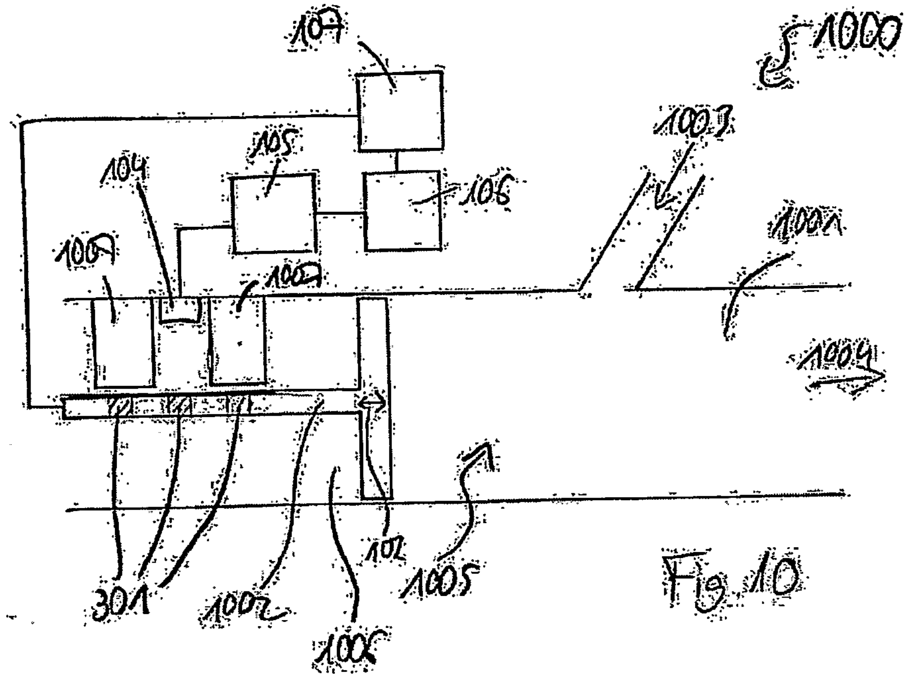
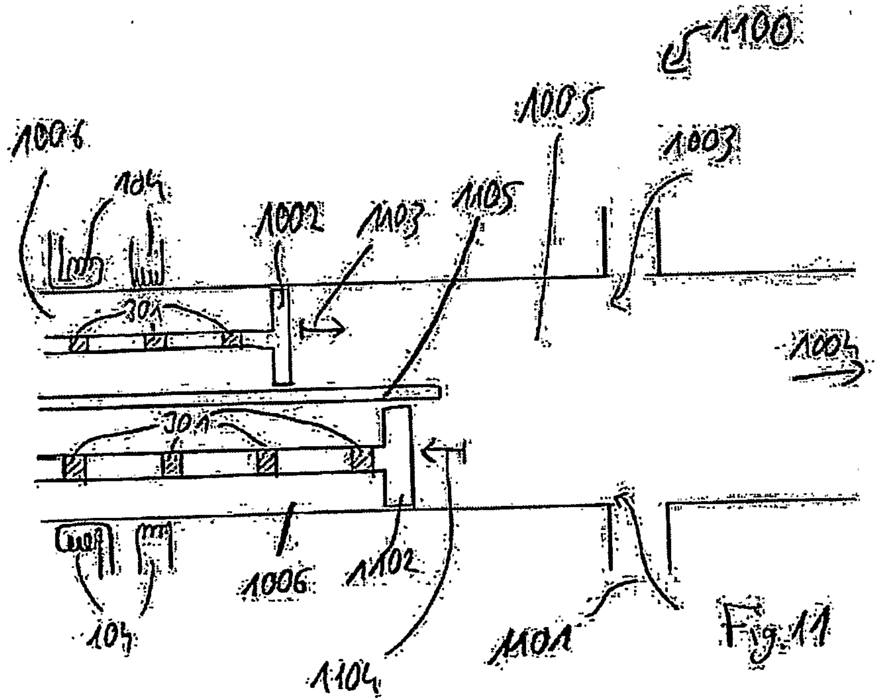


Fig 9


1000
107
105
106
104
1007
1003
1001
1004
301
1002
1006
102
1005
Fig. 10


1100
1005
1003
1006
104
1002
1103
1105
301
1004
301
104
1006
1102
1104
1101
Fig. 11

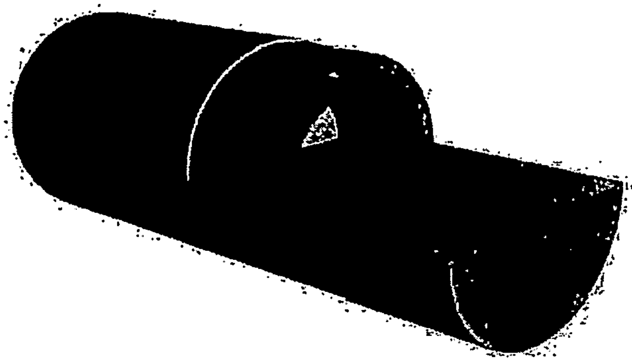


Fig. 12

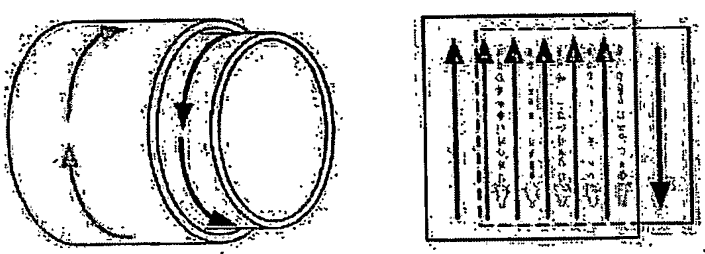


Fig. 13

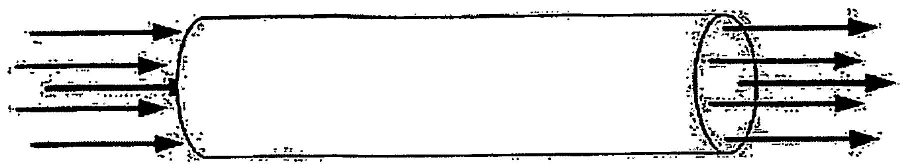


Fig 17

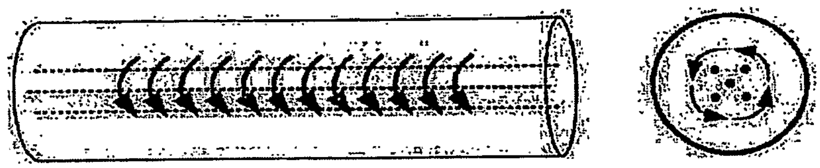


Fig 18

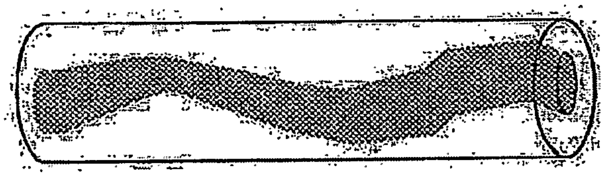


Fig 19

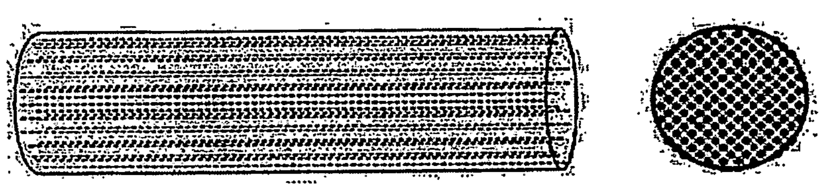


Fig 20

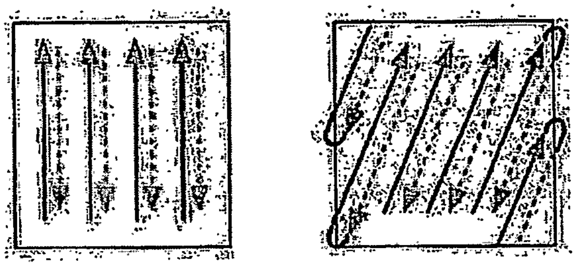


Fig 14

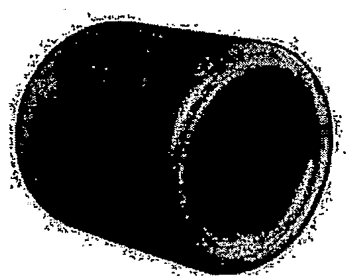


Fig 15

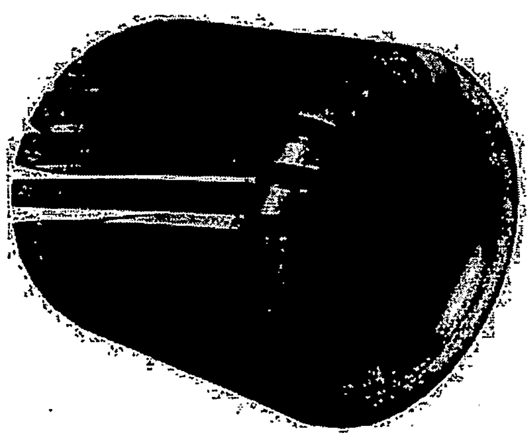


Fig 16

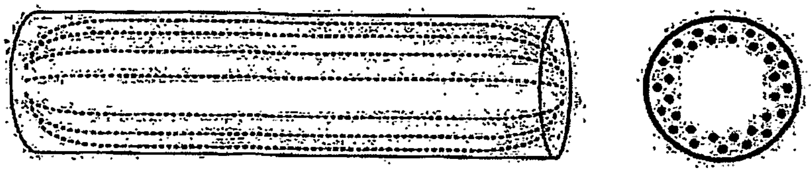


Fig 21

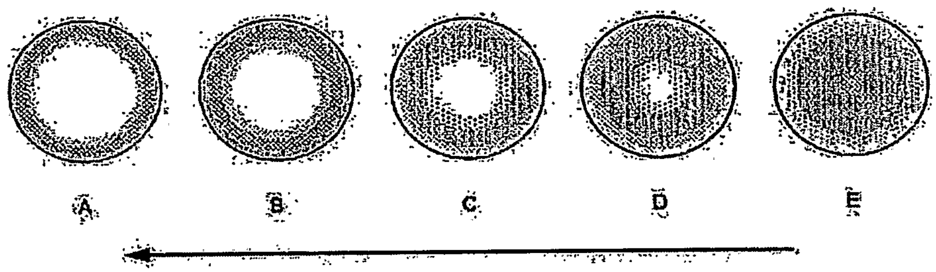


Fig 22

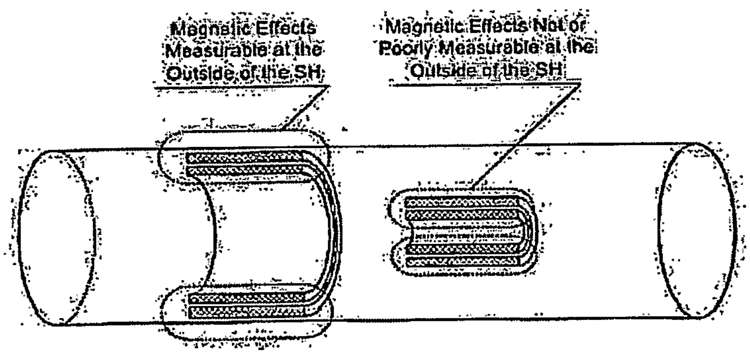


Fig 23

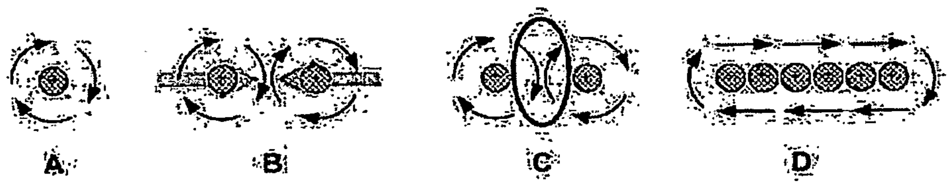


Fig 24

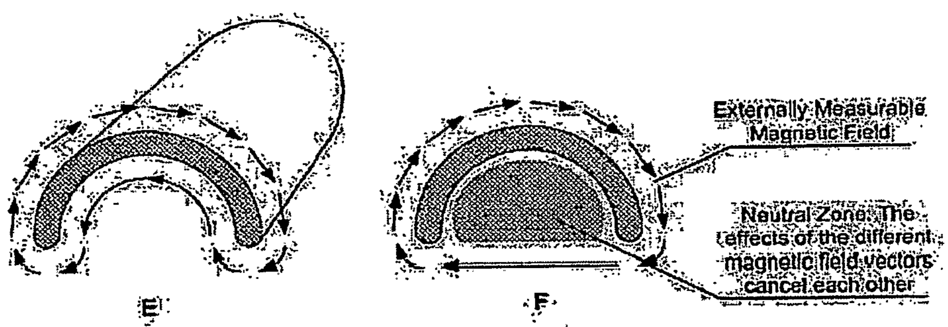


Fig 25

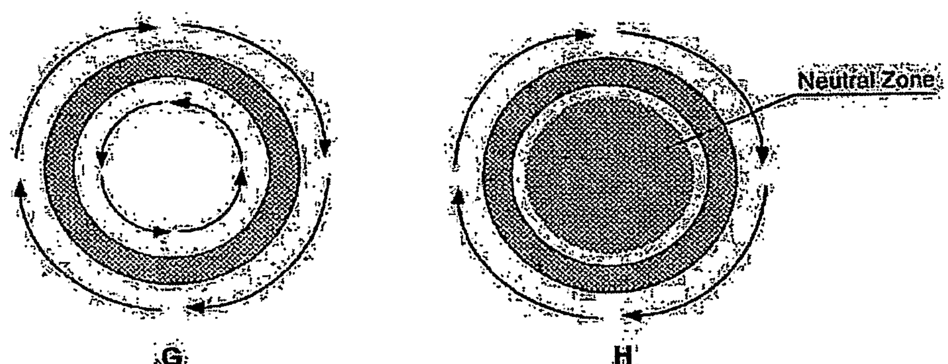
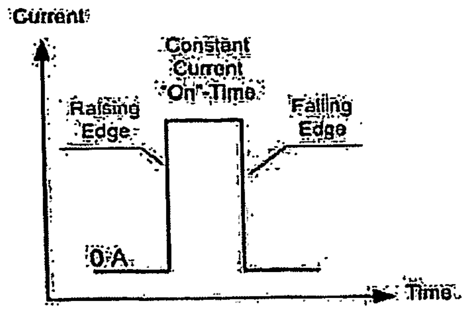
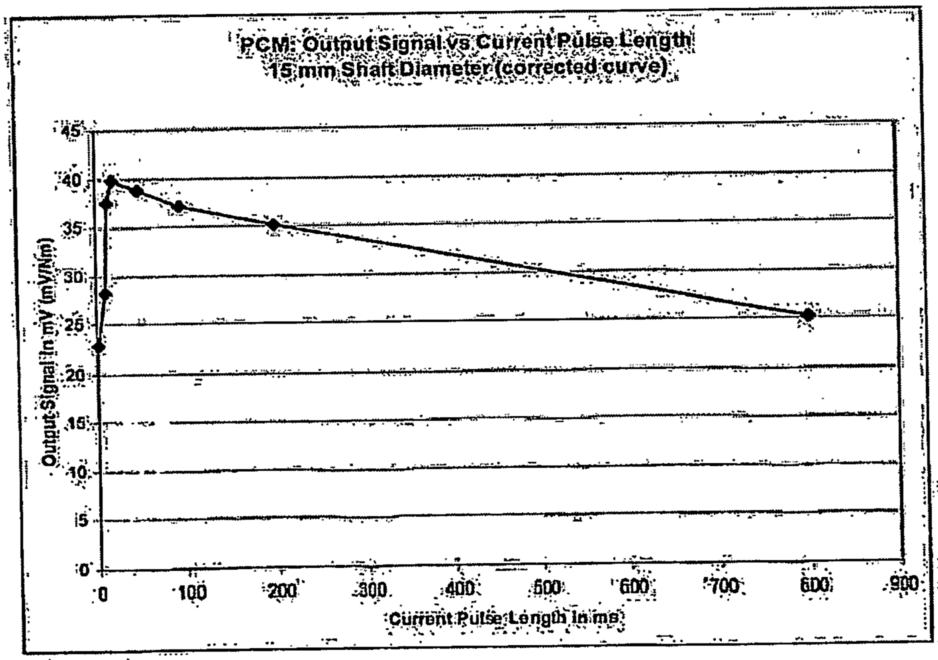


Fig 26



Current
Constant
Current
"On"-Time
Raising
Edge
Falling
Edge
0 A
Time

Fig. 27



PCM: Output Signal vs Current Pulse Length
15 mm Shaft Diameter (corrected curve)
Output Signal in mV (mV/Nm)
45
40
35
30
25
20
15
10
5
0
0
100
200
300
400
500
600
700
800
900
Current Pulse Length in ms

Fig. 28

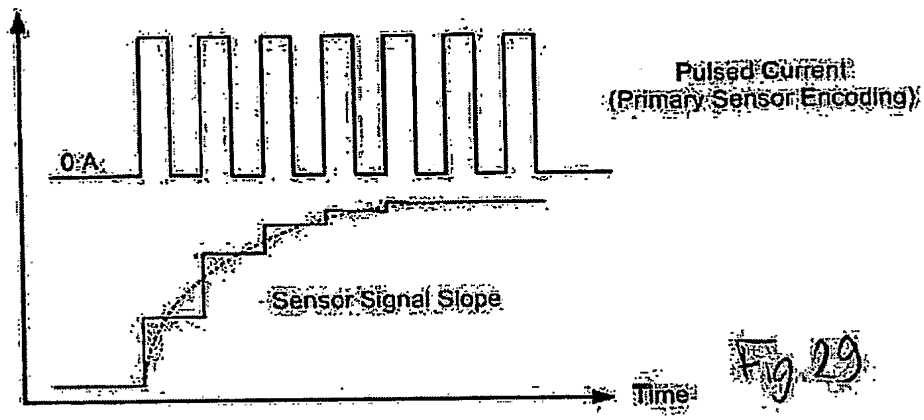


Fig 29

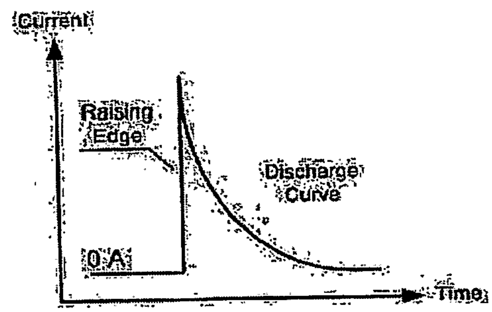


Fig 30

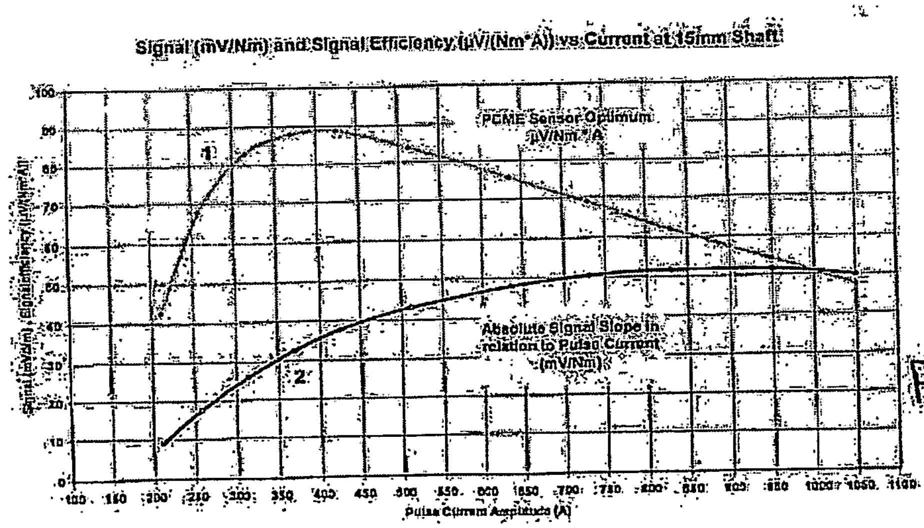


Fig 31

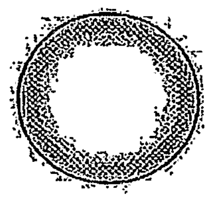


Fig 32

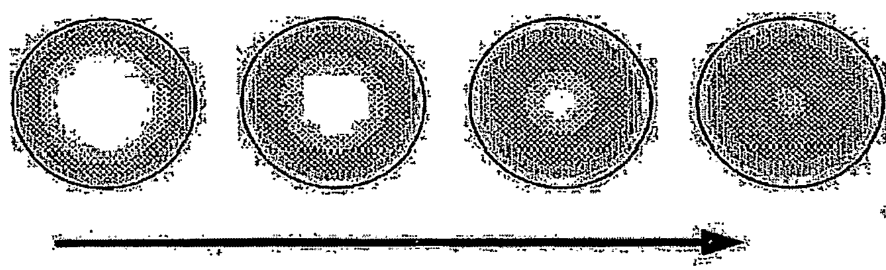


Fig 33

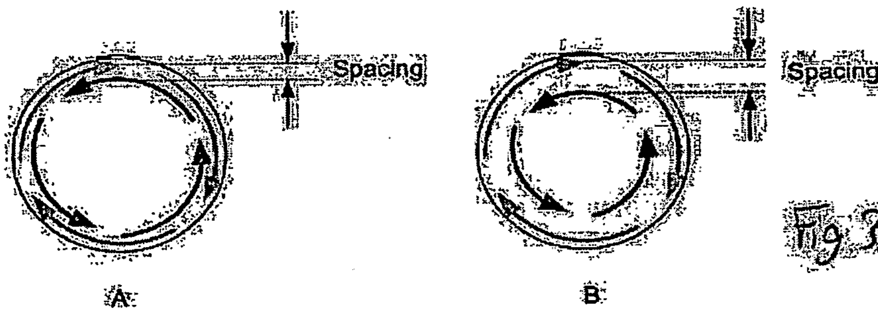


Fig 34

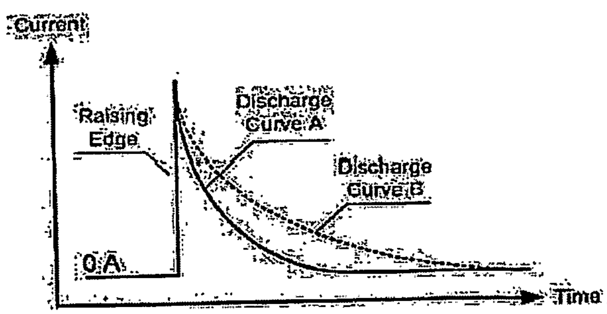


Fig 35

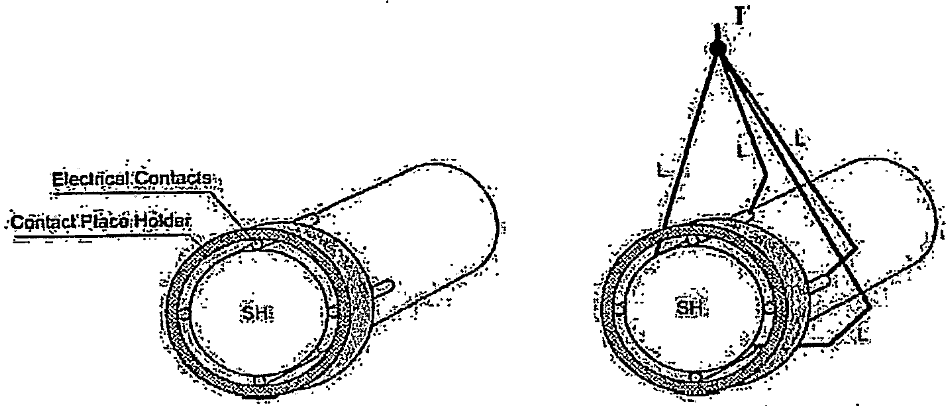


Fig 36

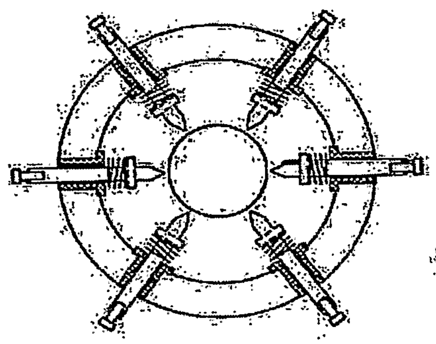


Fig 37

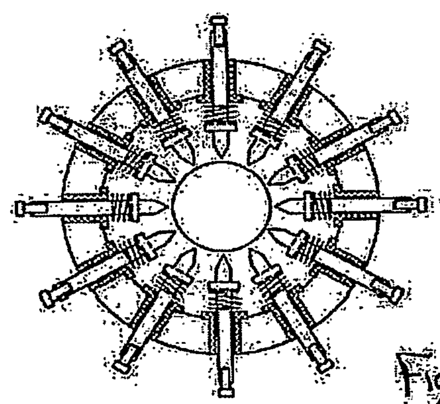


Fig 38

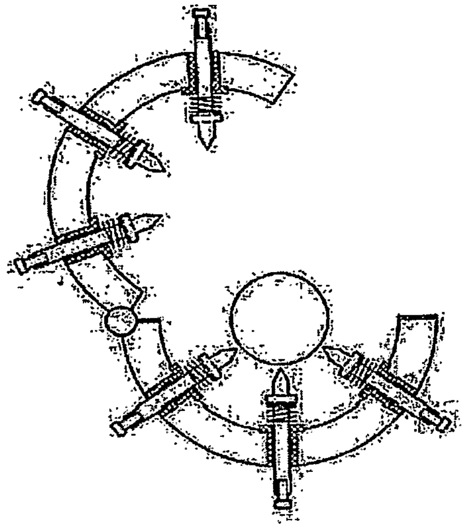


Fig 39

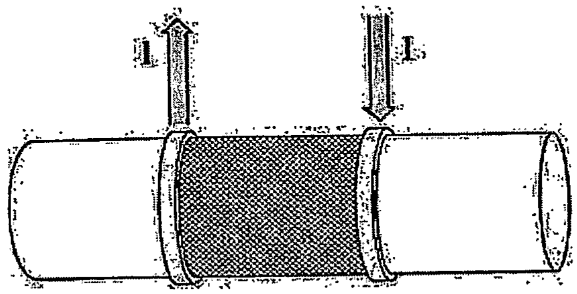


Fig 40

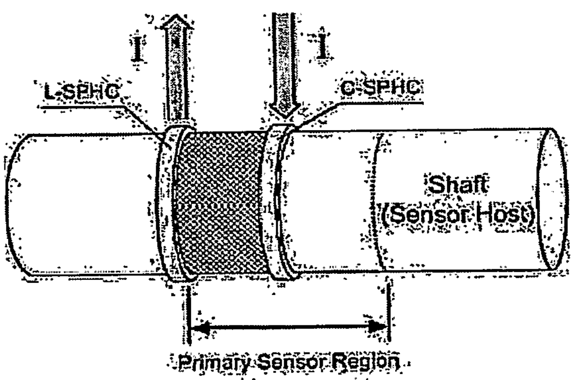


Fig 41

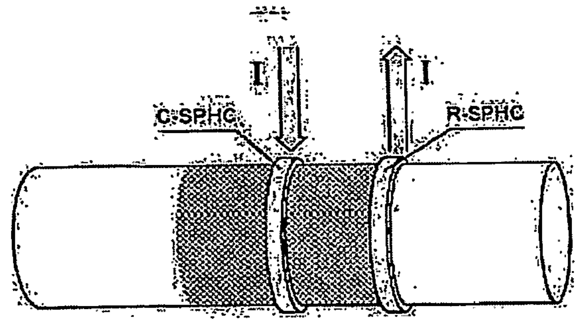


Fig 42

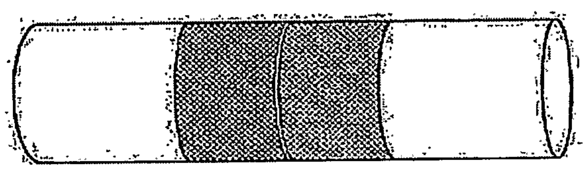


Fig 43

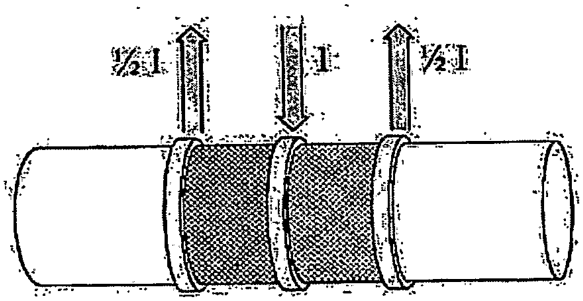


Fig 44

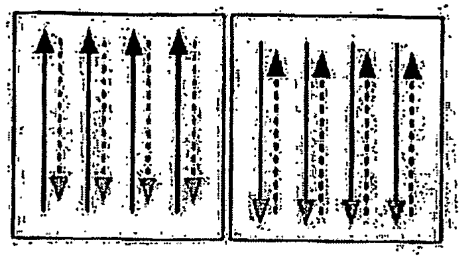


Fig 45

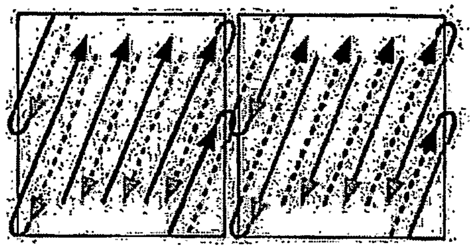


Fig 46

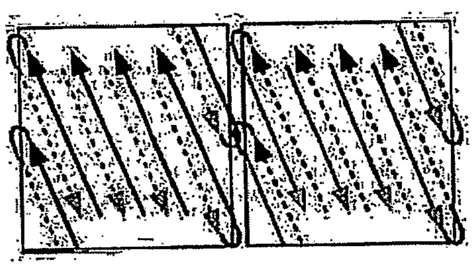


Fig 47

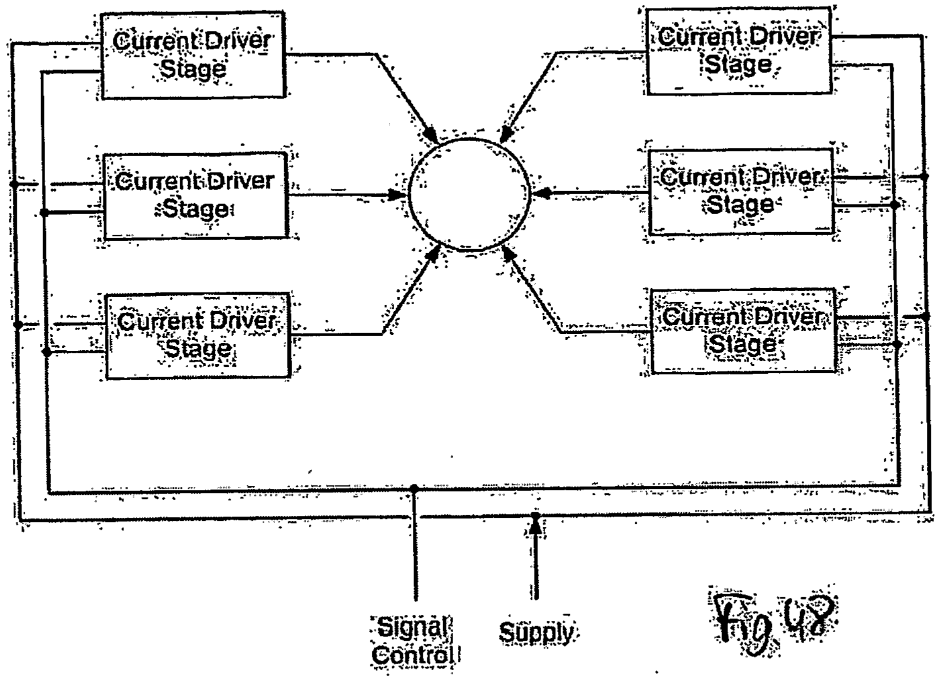

Current Driver Stage
Current Driver Stage
Current Driver Stage
Current Driver Stage
Current Driver Stage
Current Driver Stage
Signal Control
Supply

Fig 48

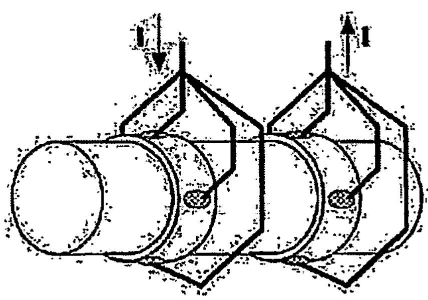

I
I

Fig 49

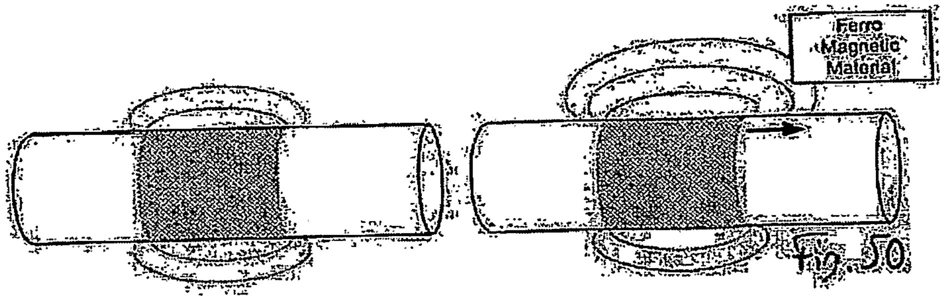


Fig. 50

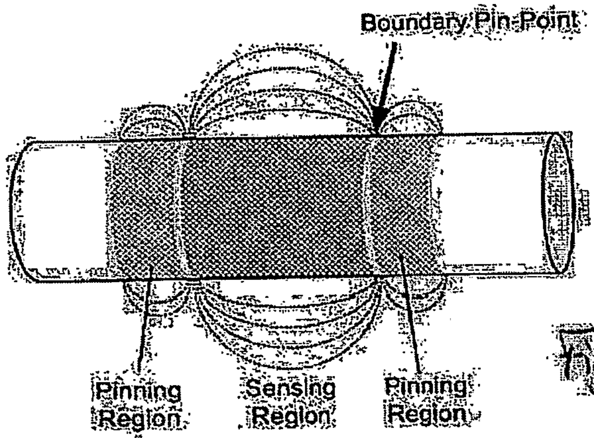


Fig. 51

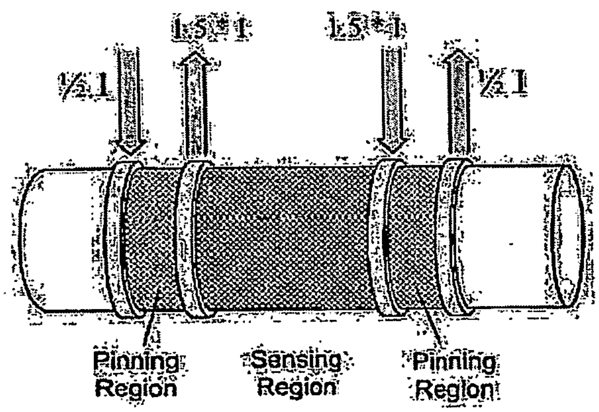


Fig. 52

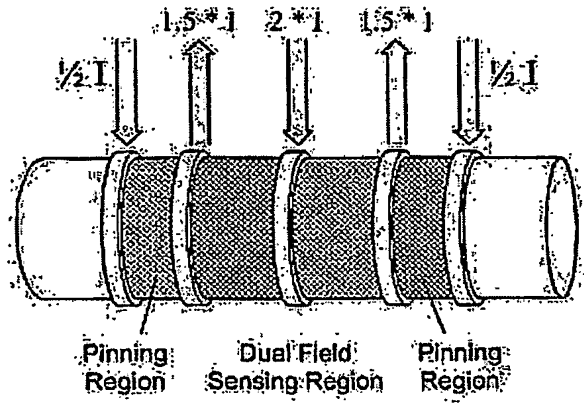


Fig 53

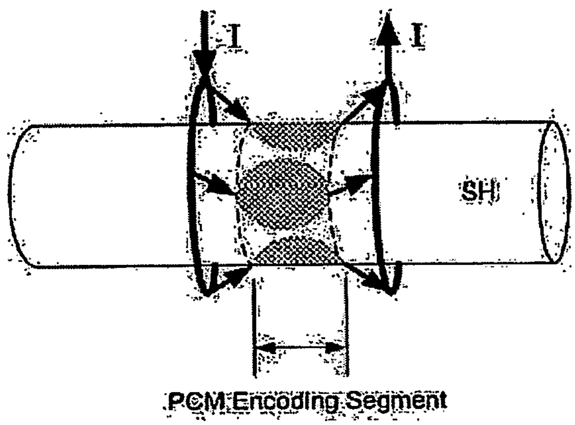


Fig 54

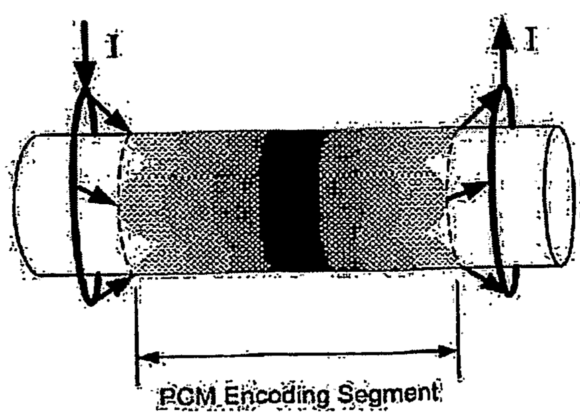


Fig 55

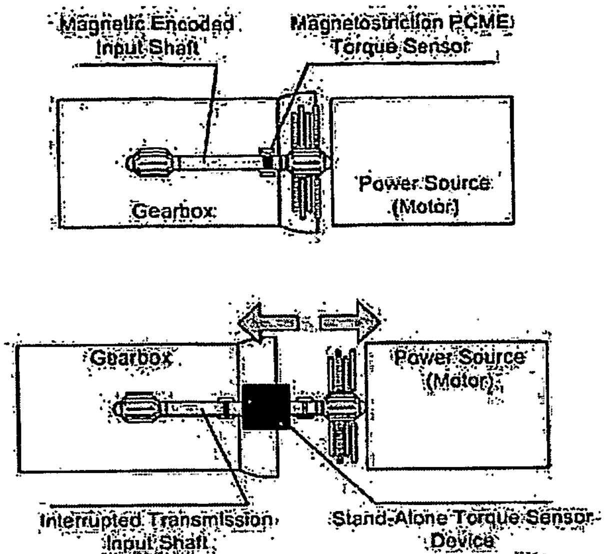

Magnetic Encoded Input Shaft
Magnetostriction PCME Torque Sensor
Gearbox
Power Source (Motor)
Gearbox
Power Source (Motor)
Interrupted Transmission Input Shaft
Stand-Alone Torque Sensor Device

Fig. 56

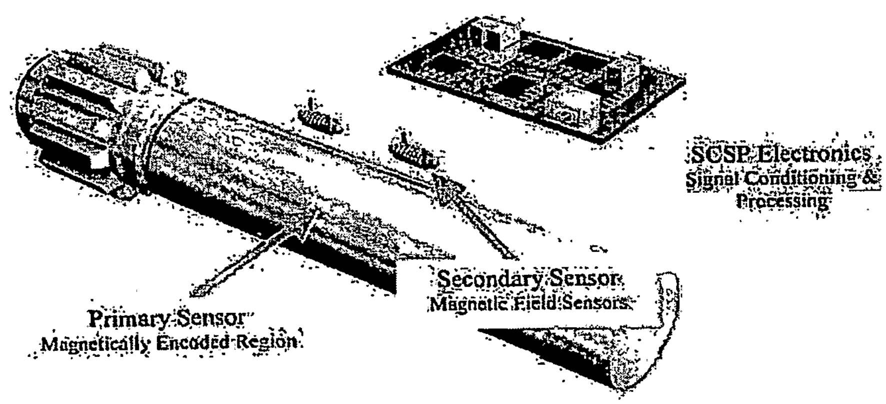

SCSP Electronics
Signal Conditioning & Processing
Secondary Sensor
Magnetic Field Sensors
Primary Sensor
Magnetically Encoded Region

Fig. 57

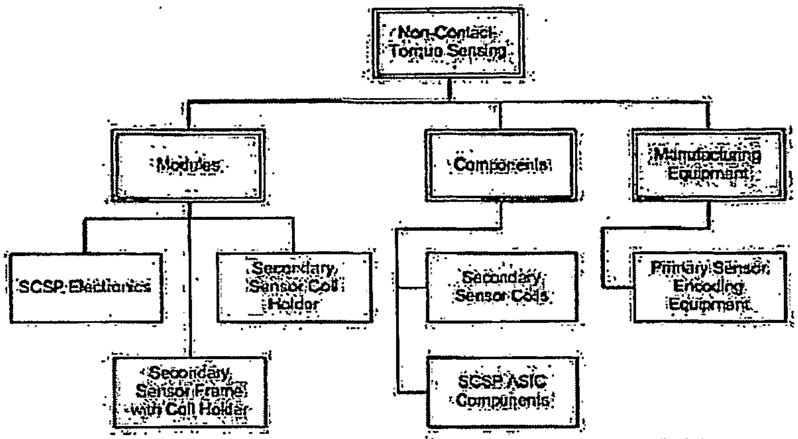


Fig. 58

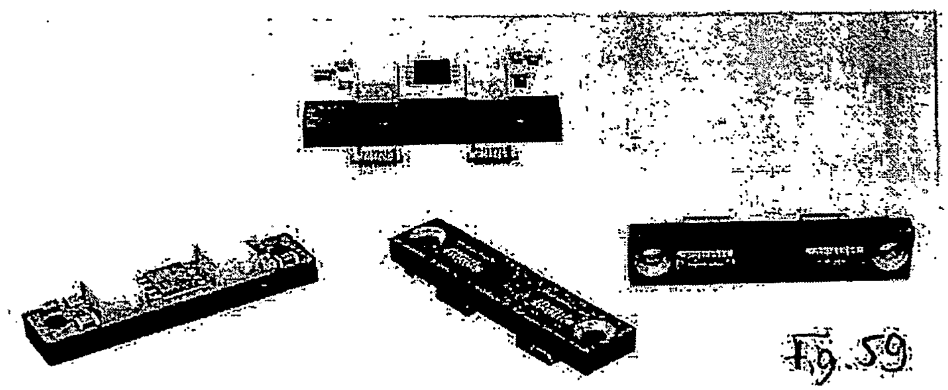


Fig. 59

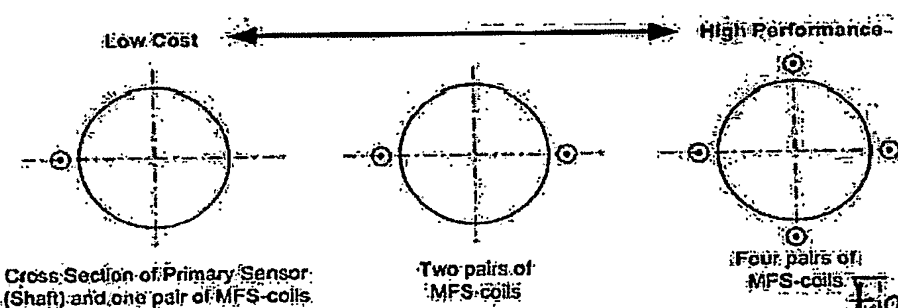


Fig. 60

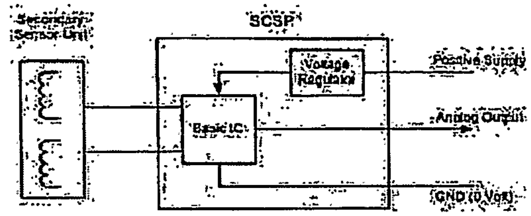

Secondary Sensor Unit
SCSP
Voltage Regulator
Positive Supply
Basic IC
Analog Output
GND (0 Volt)

Fig 61

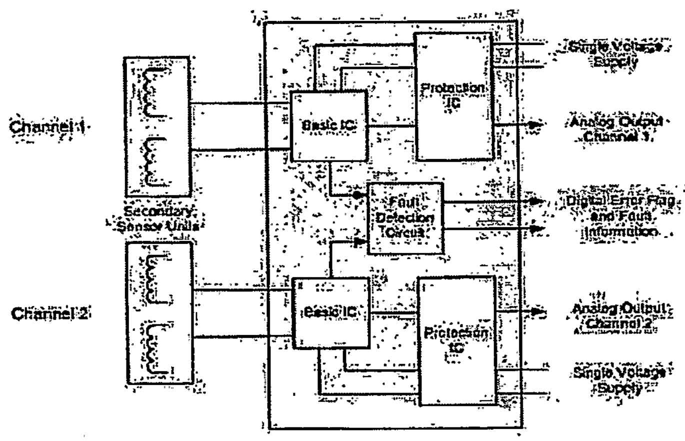
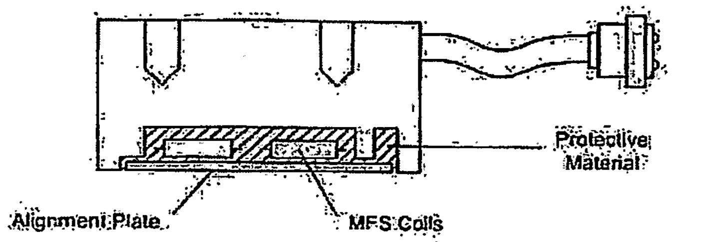
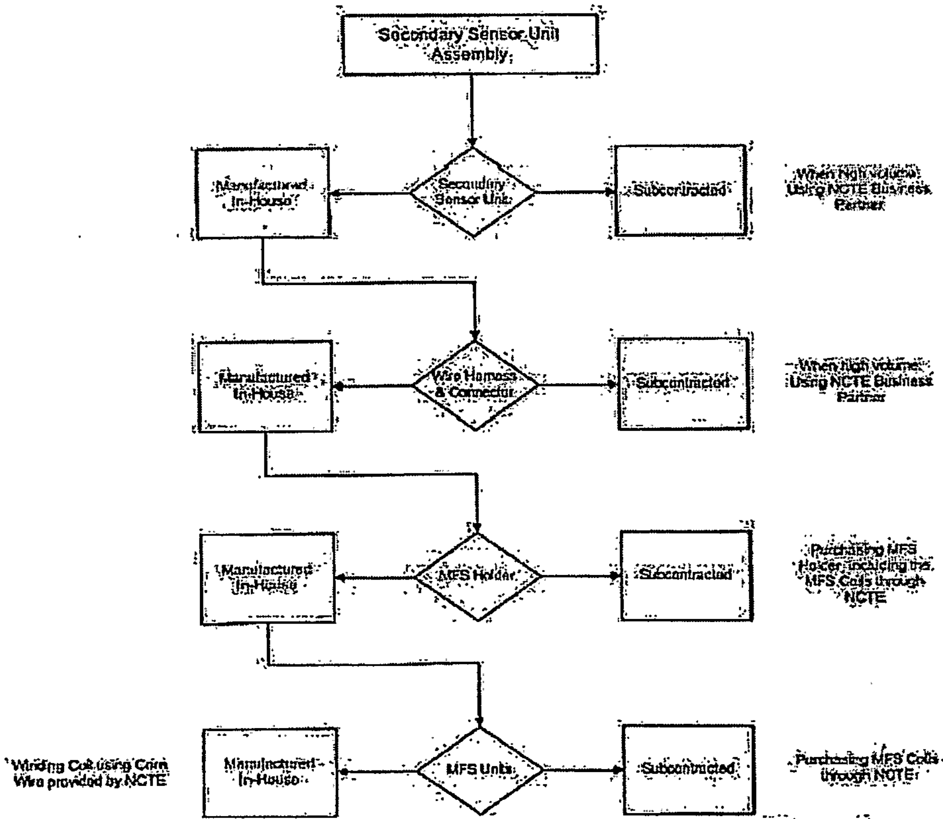

Single Voltage Supply
Protection IC
Channel 1
Basic IC
Analog Output Channel 1
Fault Detection Circuit
Digital Error Flag and Fault Information
Secondary Sensor Units
Channel 2
Basic IC
Protection IC
Analog Output Channel 2
Single Voltage Supply

Fig 62



SSU Housing
Wire Harness & Connector
Protective Material
Alignment Plate
MFS Coils

Fig. 63



Secondary Sensor Unit Assembly
Manufactured In-House
Secondary Sensor Unit
Subcontracted
Wire Harness & Connector
MFS Holder
MFS Units
When high volume Using NCTE Business Partner
Purchasing MFS Holder including the MFS Coils through NCTE
Winding Coil using Core Wire provided by NCTE
Purchasing MFS Coils through NCTE

Fig. 64

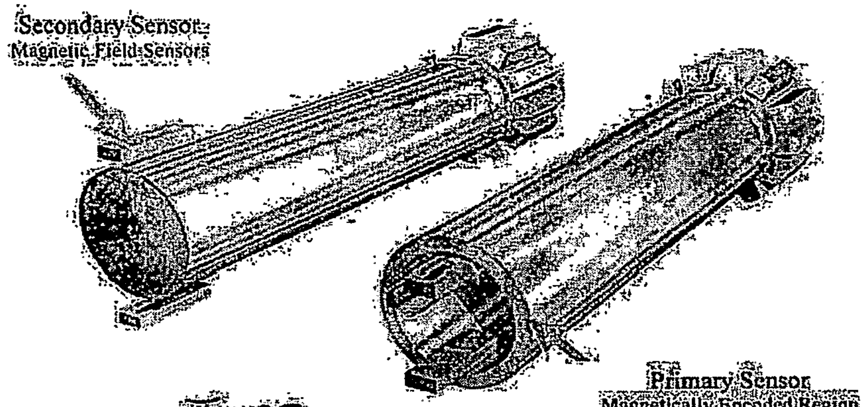

Secondary Sensor
Magnetic Field Sensors
Primary Sensor
Magnetically Encoded Region

Fig 65

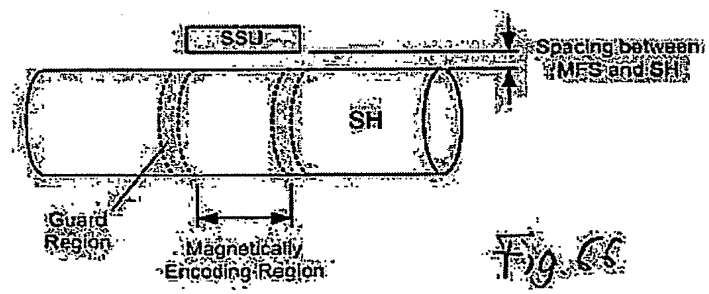

SSU
Spacing between MFS and SH
SH
Guard Region
Magnetically Encoding Region

Fig 66

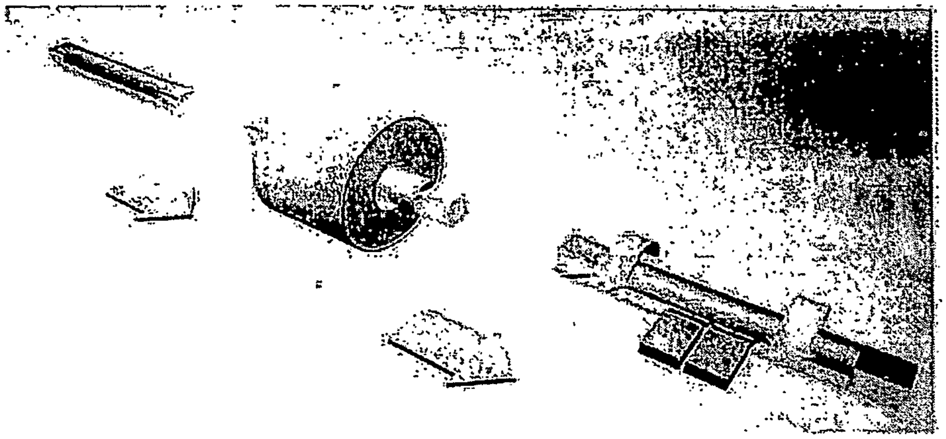


Fig. 67

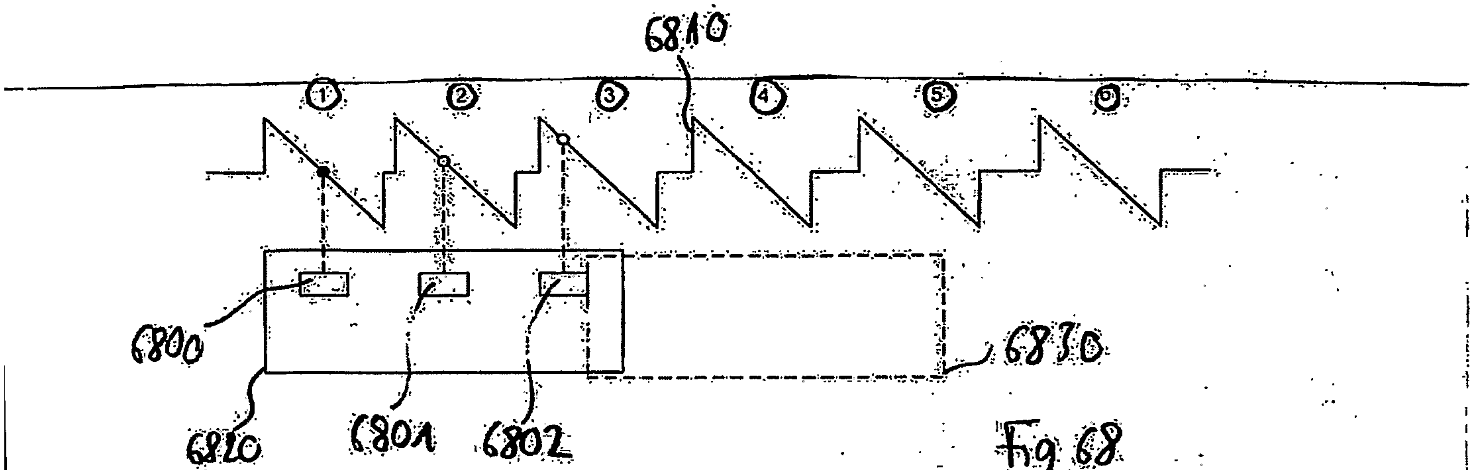


Fig 68

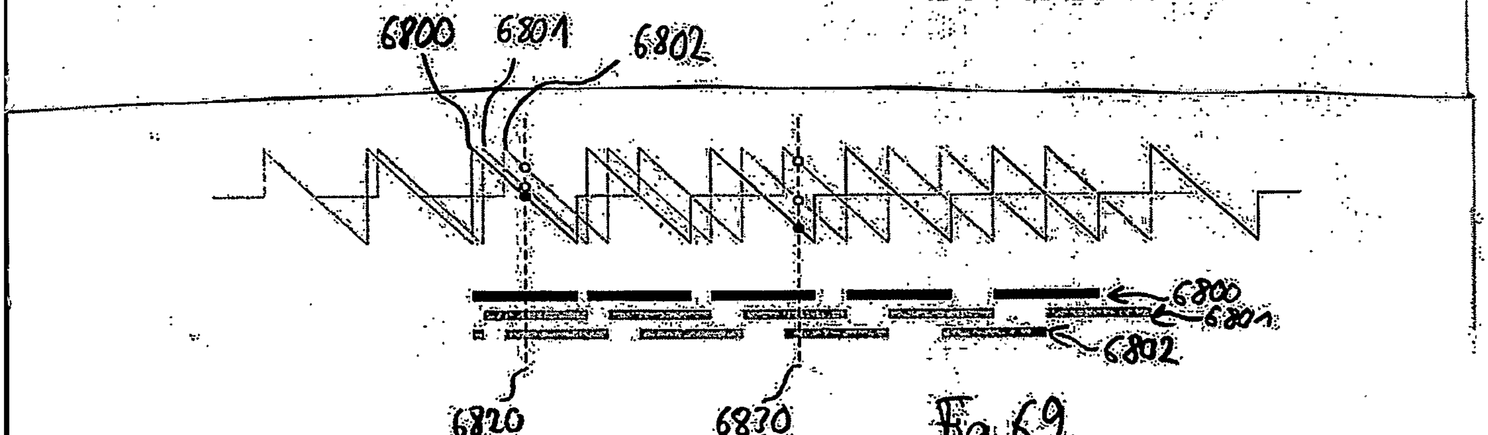


Fig 69

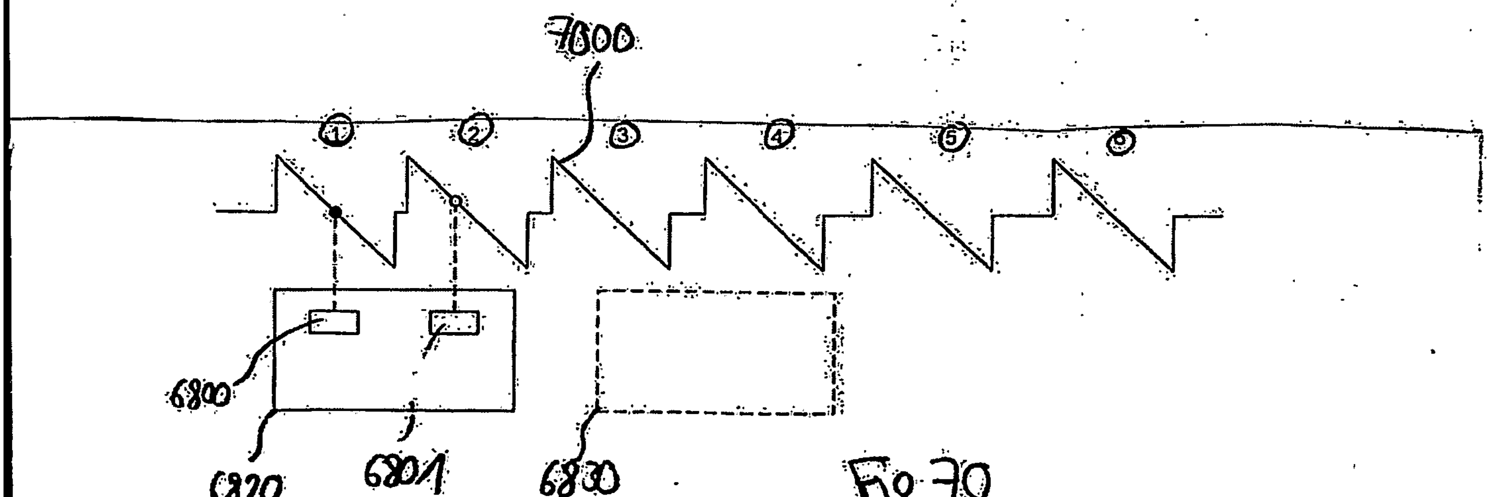


Fig. 70

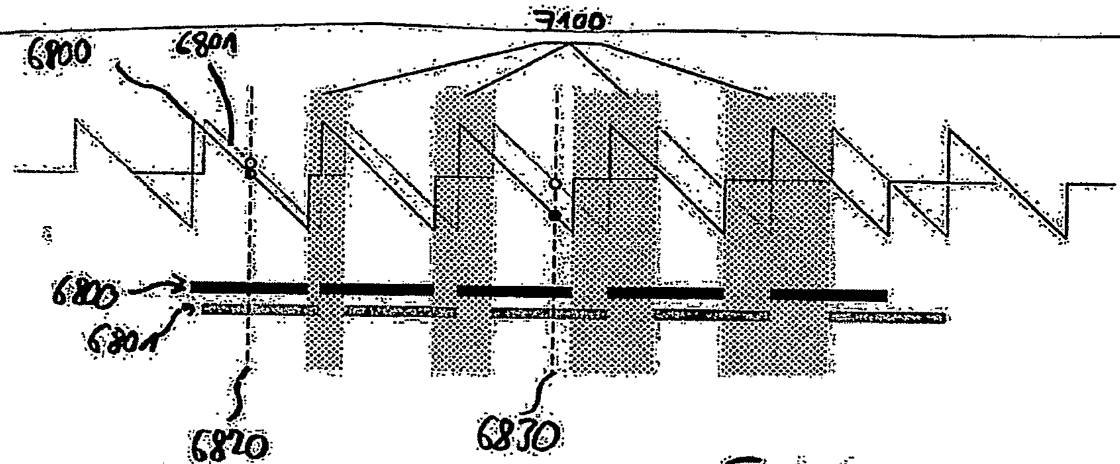


Fig 71

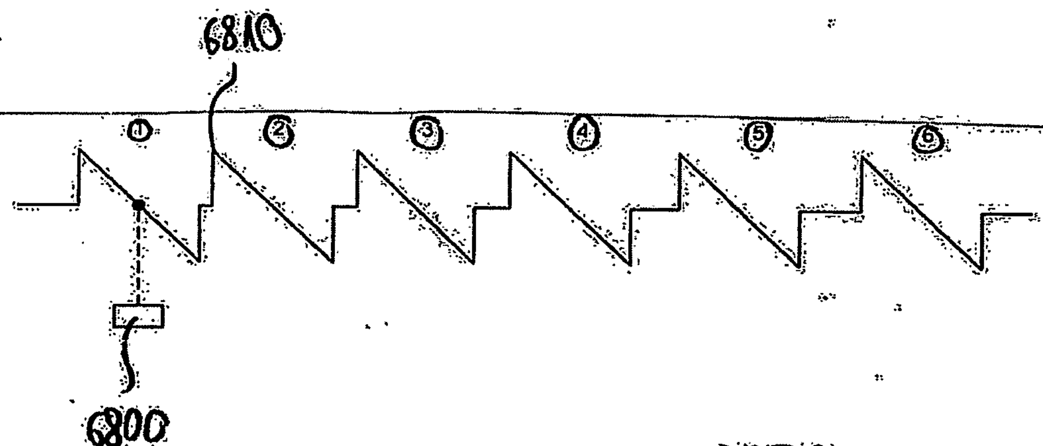


Fig 72

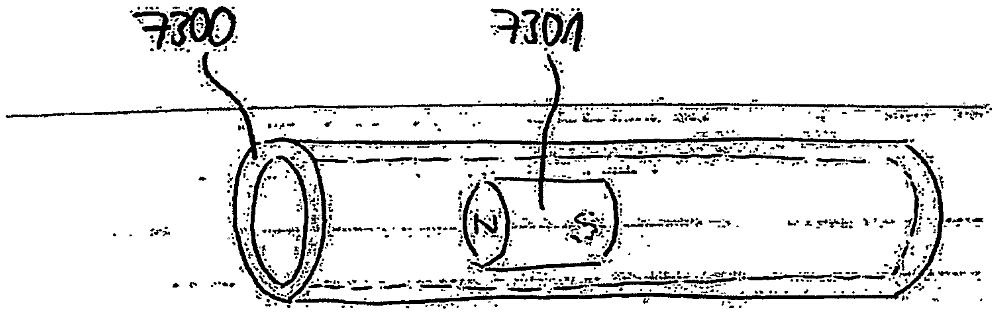


Fig 73

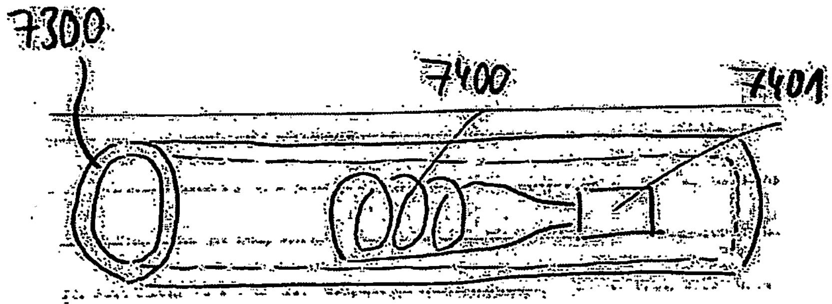


Fig 74

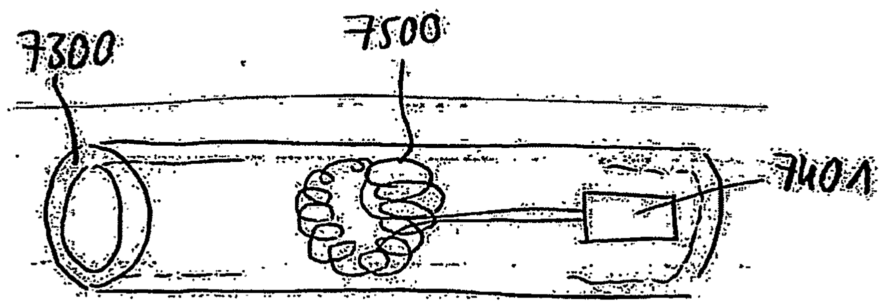


Fig 75

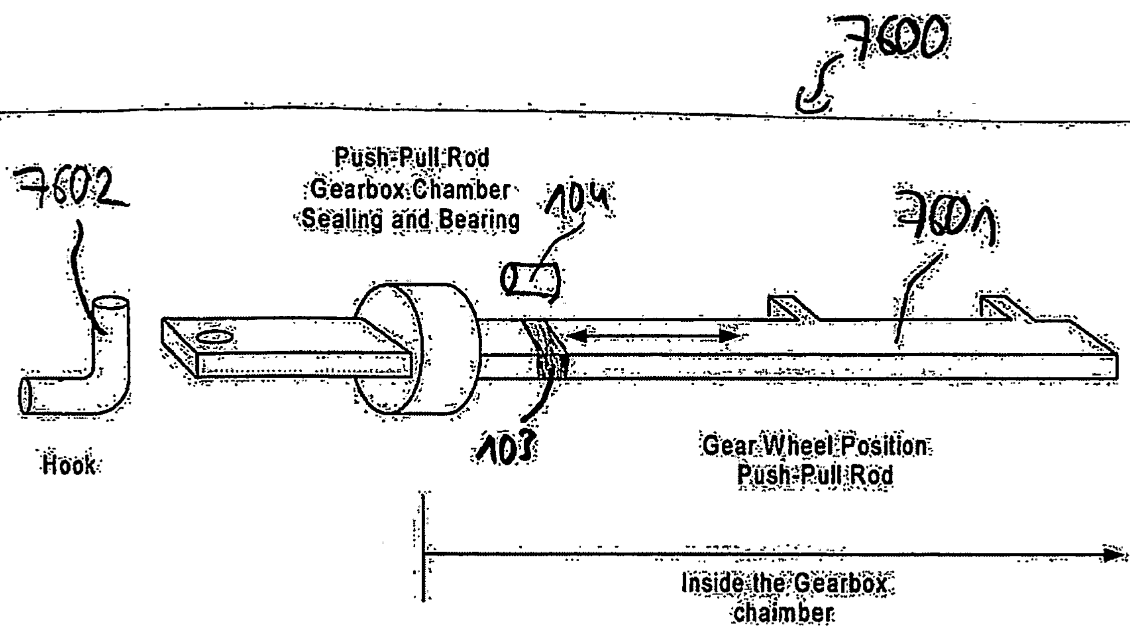

7600
7602
Push-Pull Rod
Gearbox Chamber
Sealing and Bearing
104
7601
Hook
103
Gear Wheel Position
Push-Pull Rod
Inside the Gearbox
chaimber

Fig.76

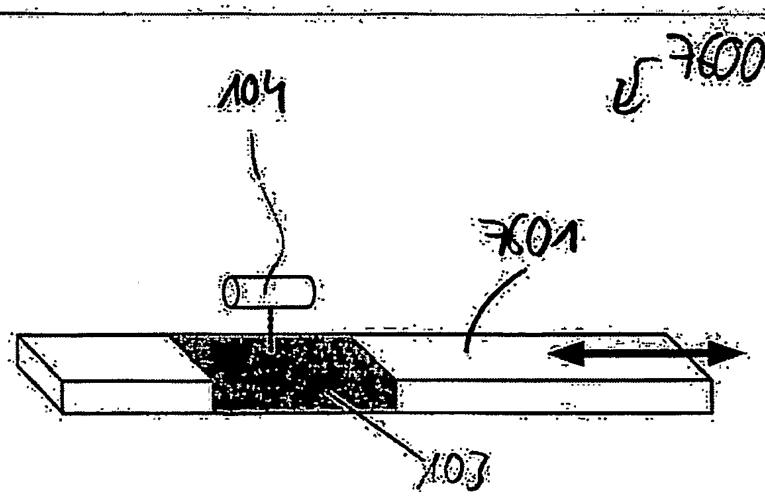

7600
104
7601
103

Fig.77

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APPLICATION NUMBER: ***60/598,111***
FILING DATE: ***August 02, 2004***

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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Inventor(s)	:	**Lutz MAY** **Wolfratshauser Strasse 23a** **82578 Geretsried-Gelting** **Germany**
Serial No.	:	**To Be Assigned**
Filing Date	:	**Herewith**
For	:	**Wireless Sensor Power Supply and Signal Read-Out**

Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450
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Signature

Please associate this Application (Attorney Docket No. 40124/03601) with Customer No. 30636

U.S. PROVISIONAL APPLICATION REQUEST TRANSMITTAL

SIRS:

Enclosed herewith please find the following:

1. 37 sheets of Specification
2. Returned Receipt Postcard.

Please charge the deposit account of **Fay Kaplun & Marcin, LLP No. 50-1492** in the amount of **$160.00**. The Commissioner is hereby authorized to charge the payment of any additional fees associated with this communication or arising during the pendency of this application to the Deposit Account of Fay Kaplun & Marcin, LLP. A copy of this Transmittal is submitted for this purpose.

Date: August 2, 2004

By: ______________________
Oleg F. Kaplun (Reg. No. 45,559)

Fay Kaplun & Marcin, LLP
150 Broadway, Suite 702
New York, NY 10038
Tel: 212-619-6000
Fax: 212-619-0276

[40124/03601]

U.S. PROVISIONAL PATENT APPLICATION

For

WIRELESS SENSOR POWER SUPPLY AND SIGNAL READ-OUT

Inventor(s):
Lutz MAY

Total Pages (including title page and specification): **37**

Represented by:

FAY KAPLUN & MARCIN, LLP
150 Broadway, Suite 702
New York, NY 10038
(212) 619-6000 (tel)
(212) 619-0276 (fax)
info@FKMiplaw.com

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Name: Oleg F. Kaplun, Reg. No. 45,559

Signature

NCTE (NCTEngineering GmbH) is a sensor engineering and manufacturing company in Ottobrunn near Munich, founded in 2003. NCTE stands for Non Contact Torque Engineering.

The engineering team from NCTE has supported the motor sport market for the last 8 years in providing F1 teams and selected industries with Non-Contact-Torque sensors.

NCTE is using its patented "PCME" sensing technology, applied to an already existing input / output shaft, to measure absolute torque (and other physical parameters) with a signal bandwidth of 10 kHz and a repeatability of 0.01%. The systems total electrical current consumption is below 8 mA.

Features and performances of a NCTE torque sensor for motor sport

Parameter	Conditions	min	Typ	max	Units
Torque Measurement Range	Full Scale Measurement Range	+/- 1		+/- 7000	Nm
Signal Bandwidth	Customer Definable	100		>10,000	Hz
Signal Resolution (analog output signal)	Is a function of signal bandwidth	Equivalent to 12		Equivalent to 16	Bit
Measurement Repeatability			0.01		%
Allowable Shaft Rotation		Stationary		100,000	rpm
Electrical Supply Voltage	Single Supply Voltage		5.00		V
Electrical Supply Current	One measurement channel with analog output Voltage	4.8	6	8	mA
Operating Temp Range	Primary Sensor	-50		+210	^{0}C
Operating Temp Range	Secondary Sensor	-50		+125	^{0}C

The primary sensor system is resistive to water, gearbox oil, and non-corrosive / non-Ferro-magnetic materials. This technology can be applied to solid or hollow Ferro magnetic shafts as they are used in motor sport applications (examples: 50NiCr13, X4CrNi13-4, 14NiCr13, S155, FV520b, ..).

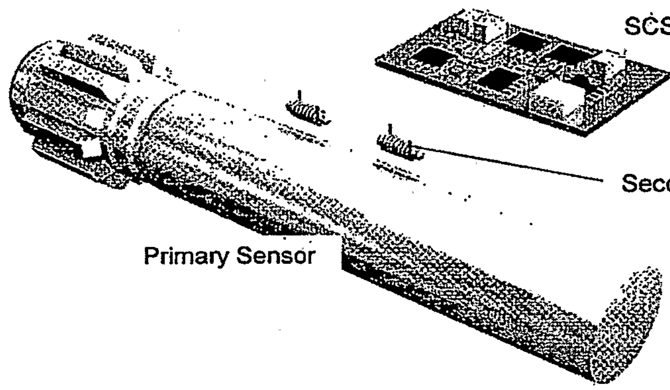
No mechanical changes are necessary on the input / output shaft (primary sensor), nor will be anything attached or glued to the shaft in any way. The input / output shaft keeps all of its mechanical properties when the NCTE technology will be applied.

In a typical motor sport program NCTE requires around 20 working days to apply its torque sensing technology to a new custom application. The turn-around supply time for a system that has been already developed is typically less then three days (re-ordering of processed Primary Sensors).

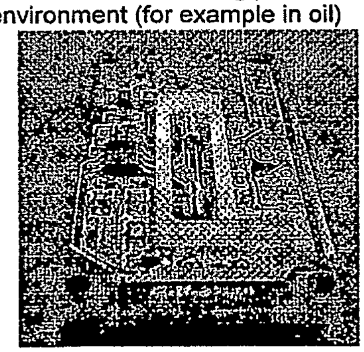
The three main modules of an NCTE sensor

A NCTE sensing system consists of three main building blocks (or modules): the **Primary Sensor**, the **Secondary Sensor**, and the **SCSP** (Signal Conditioning & Signal Processing) electronics.

The **Primary Sensor** is a magnetically encoded region at the power transmitting shaft. The encoding process is performed "one" time only (before the final assembly of the power transmitting shaft) and is permanent. The power transmitting shaft is also called Sensor Host (or **SH**) and has to be manufactured from Ferro magnetic material. In general, industrial steels that include around 2% to 6% Ni will be a good basis for the NCT sensor system. The Primary Sensor converts the changes of the physical stresses applied to the SH into changes of the magnetic signature that can be detected at the surface of the magnetically encoded region. The SH can be solid or hollow.



The **Secondary Sensor** is a number of Magnetic Field Sensor (**MFS**) devices that are placed nearest to the magnetically encoded region of the SH. However, the MFS devices do not need to touch the SH so that the SH can rotate freely in any direction. The Secondary Sensor converts changes of the magnetic field (caused by the Primary Sensor) into electrical information. NCTE is using passive MFS devices (coils) as they can be used in harsh environment (for example in oil) and operates in a very wide temperature range.

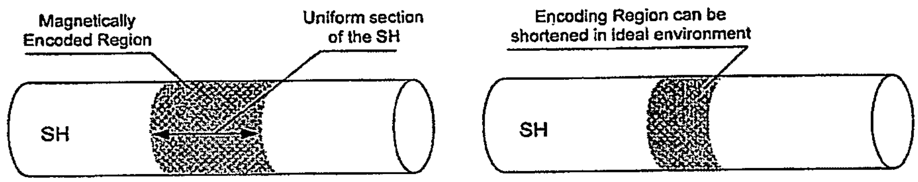


The **SCSP** (Signal Conditioning & Signal Processing) electronics drives the MFS coils and provides the user with a standard format signal output. The SCSP electronics will be connected through a twisted pair cable (2 wires only) to the MFS coils and can be placed up to 2 Meters away from the MFS coils. The SCSP electronics from NCTE is custom designed and has a typical current consumption of 5 mA.

Primary Sensor Design: Magnetically Encoded Region

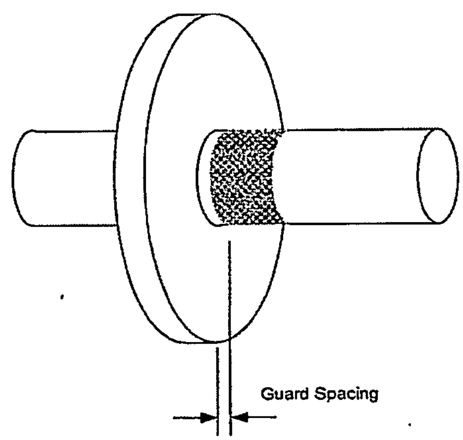
The magnetic encoding process from NCTE is relative flexible and can be applied to shafts (SH) with a diameter ranging from less than 2 mm to greater than 200 mm. The SH can be hollow or solid as the signal can be detected equally on the outside and on the inside of a hollow shaft.

In a sensor system where the SH has to be able to rotated the Encoding Region can be placed anywhere along the SH as long as the chosen location is of uniform (round) shape and does not change in diameter for a few millimeters. The axial length of the Encoding Region depends on the: SH diameter, the environment, and the expected system performances. In general a longer Encoding Region provides better results (improved signal-to-noise ration) then a shorter Encoding Region.



For example, for a SH with a diameter of less than 10 mm the magnetic Encoding Region should not be longer than 25 mm and can be as short as 10 mm (always assuming under ideal circumstances.

For a shaft of 30 mm diameter the magnetic Encoding Region can be as long as 60 mm. When the SH diameter increases further it becomes difficult to produce fully functional Encoding Regions that are very short in length, near the 10 mm length.



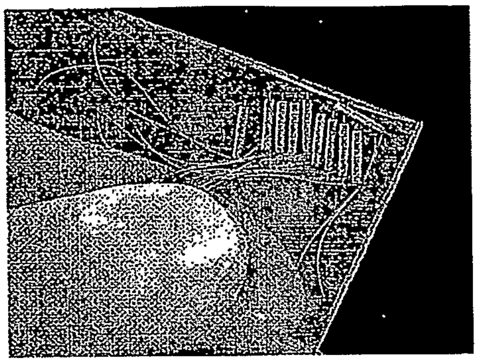
The Encoded Region has to have several millimeters spacing (Guard Spacing) from other Ferro magnetic objects that are placed at or near the Encoded Region. The same is true when the shape or the shaft diameter is changing at either side of the Encoded Region.

Primary Sensor Material Suggestion

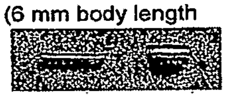
Rank	DIN	Specification
1	1.2721	50NiCr13
2	1.4313	X4CrNi13-4
3	1.4542	X5CrNiCuNb16-4
4	1.2787	X20CrNi17-4
5	1.4034	X46Cr13
6	1.4021	X20Cr13
7	1.5752	14NiCr14
8	1.6928	S155

Secondary Sensor unit: MFS coil dimensions

NCTE is using very small inductors (also called: Magnetic Field Sensors or MFS) to detect the magnetic information coming from the primary sensor. The dimensions and specifications of these coils are adapted and optimized for the PCME sensing technology and the targeted application.

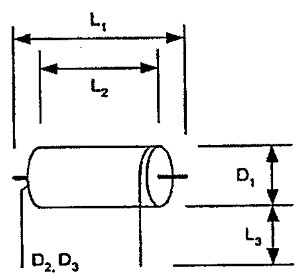


The MFS from NCTE come in two different sizes (6 mm body length and 4 mm body length), and two different temperature ranges (standard temperature range till 125 deg C, and high temperature range till 210 deg C). Further dimensions are listed in the table below.



The electrical performance of the 4mm and the 6 mm coil are very similar, whereby one is a bit longer and the other has a slightly larger diameter. The wire used to make the coil is relatively thin (0.080 mm in diameter, incl. insulation) and is therefore delicate.

Specification	Sym	6mm Coil	4mm Coil	Unit
Length overall	L_1	8.00 +/-0.2	6.1 +/-0.2	mm
Body length	L_2	6.00 +/-0.2	4.1 +/-0.2	mm
Wire length	L_3	>65	>65	mm
Coil diameter	D_1	1.27 +/-0.1	2.05 +/-0.15	mm
Cu wire dim	D_2	0.065	0.065	mm
Coated wire	D_3	0.08 +/-0.005	0.08 +/-0.005	mm
Resistance	R	7.4 +/-0.5	10.5 +/-0.7	Ohm

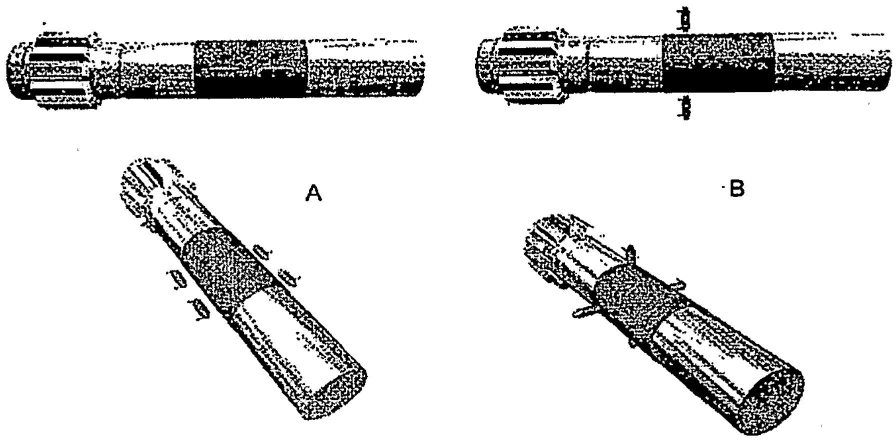


In applications where two axial aligned MFS coils are needed (for example to compensate for the effects of the Earth Magnetic stray Field, also referred to as EMF) they can be placed inside a specially milled PCB. This type of assembly (here shown with the two MFS coils before potting them) guaranties good alignment of the MFS coils and will provide reasonable mechanical protection.

How many MFS coils are needed and where they should be placed (in relation to the Encoded Region) is depending on the available physical spacing in the application and on which physical parameters should be detected or should be eliminated. In the classical NCT sensor design coils in pairs are used (see picture above) to allow differential measurement and to compensate for the effects of interfering magnetic stray fields.

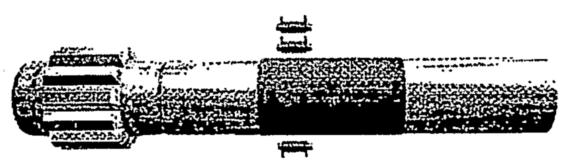
Secondary Sensor Design: MFS arrangement

Depending on the sensor environment and the targeted system performance, a NCTE sensor system can be built with only one MFS coil or with as many as 9 MFS coils. Using only one MFS coil is only advisable in a stationary measurement system where no magnetic stray fields are present. Nine MFS coils may be needed when high sensor performances expected and the sensor environment is complex (for example: interfering magnetic stray fields are present and interfering Ferro magnetic are moving nearby the sensor system).



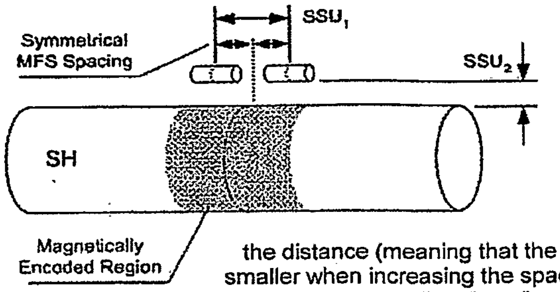
There are three axial directions with which the MFS coils can be placed near the magnetically encoded region: Axial (parallel to the SH), Radial (sticking away from the SH surface), and Tangential. The axial direction of the MFS coil and the exact location in relation to the Encoding Region defines which physical parameters are detected (measured) and which parameters are suppressed (canceled-out).

In circumstances where limited axial spacing is available to place the MFS coils near or at the Encoding Region (see above drawing, option A), the MFS coils can be placed radial, slightly off-centered to the Encoding Region (option B).



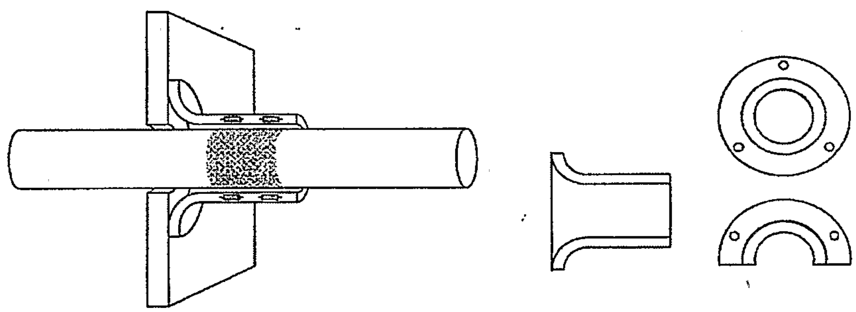
When limited axial spacing is available then single MFS-coils can be used with a "piggy-back" MFS-coil to eliminate the effects of parallel interfering magnetic stray fields (like the Earth Magnetic Field, **EMF**).

In the classical (standard) NCTE sensor design the Secondary Sensor Unit (Two MFS coils facing the same direction) is placed in axial direction (parallel) to the SH, and placed symmetrical to the center of the magnetic encoded region.



The critical dimensions are: Spacing between the two MFS coils (SSU_1), and the spacing between the SH surface and the MFS coil surface (SSU_2). When changing SSU_2 the signal output of the sensor system will change with the square to the distance (meaning that the output signal becomes rapidly smaller when increasing the spacing between the SH surface). SSU_2 can be as small as "zero" mm, and can be as large as 6 mm, whereby the signal-to-noise ratio of the output signal worsens at larger numbers.

The spacing between the two axially placed MFS coils is a function of the magnetic encoding region design. In the classical NCTE sensor design SSU_1 has to be 14 mm. This spacing can be reduced by several millimeters when accepting that the Rotational Signal Uniformity (**RSU**) performance will worsen to some degree.



The above drawing shows a typical MFS coil holder as used in gearbox applications. Note: The second MFS-coil pair improves the sensors capability in dealing with shaft run-outs (radial movements of the shaft during operation).

PCME Sensor Electronics

While it is possible to build a precision force (like torque) sensor with one MFS (Magnetic Field Sensor) device only, the PCME senor system performances greatly improve when using 2 or more MFS devices in the Secondary Sensor Unit. For example, by using two MFS devices, placed in reversed order to each other it is possible to enhance the targeted sensor signal while simultaneously the EMF (Earth Magnetic Field) or any other uniform and parallel magnetic stray field will be canceled.

The achievable performance of such a signal processing approach depends greatly on the matching of the actual electrical specifications between the used MFS devices in the Secondary Sensor Unit.

The here described inventions are electrical circuit designs that assure that the MFS devises and the attached first stage SCSP (Signal Conditioning & Signal Processing) electronics are automatically matched to each other. Meaning that when using such a circuit design as here described, any signal gain differences between two or more signal channels, caused by specification differences of the MFS devices, or caused by tolerances of the used active and passive electronic components, will be evened out.

This invention is specifically dedicated for applications like Motor Sport, Racing Cars, Engine Test Stands, or Power Tools. All of these applications have one thing in common: Lots of high frequency signal noise (signal frequencies of 100Hz and higher).

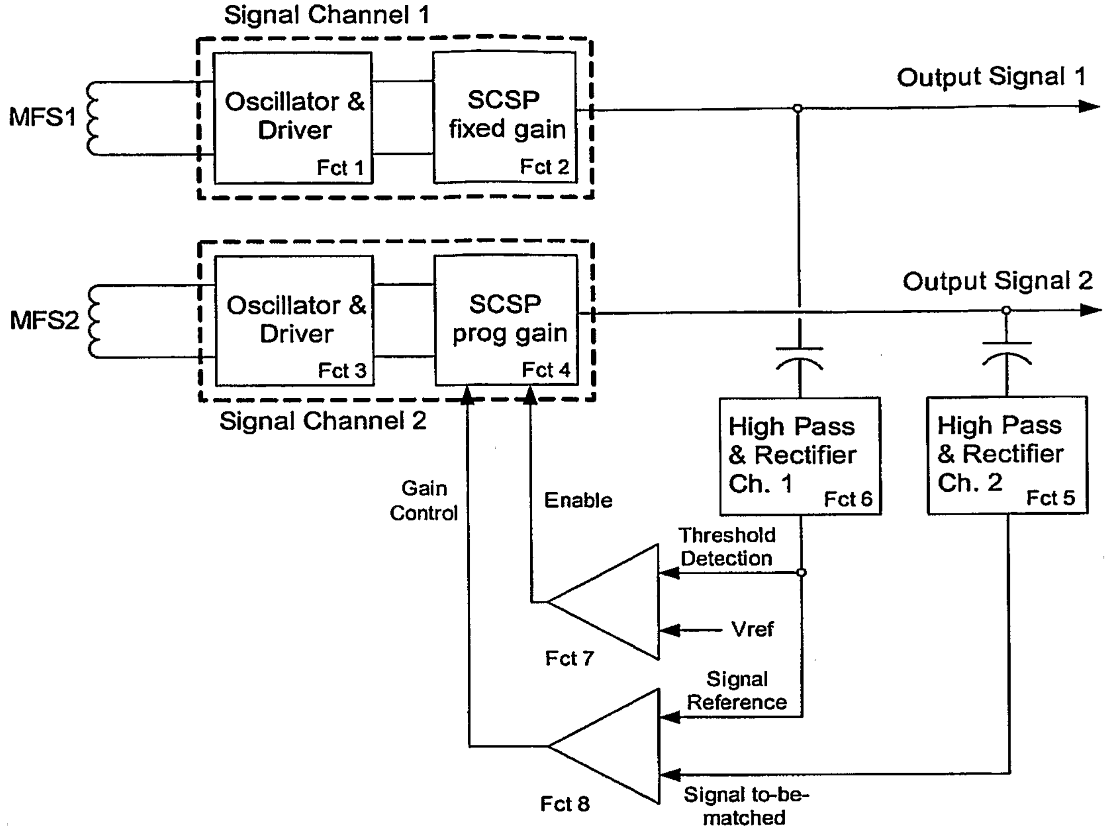
Automatic Gain Matching (AGM)

This solution, "Automatic Gain Matching" relies on the fact that there will be a lot of noise present when using this sensor in the targeted application: Motor Sport, Racing Cars, or Engine Test Stands.

When in operation the mechanical forces measured (like torque) will be very dynamic. As the used MFS devices are placed around the same Primary Sensor region, the targeted output signals should be all of the same amplitude.

Interfering magnetic stray fields have a DC or low frequency characteristics (typically 5 Hz or less). For example, a racing car that is driving around a racing track will not turn around the car in relation to the Earth Magnetic Field faster than 5 times per second (and that in itself will be astonishing already).

In the here shown example (see below) the signal gain of channel one is fixed while the signal gain of channel two can be changed through an applied voltage (Gain Control).



Drawing 1A: Automatic and active channel-gain-matching by comparing the high frequency signal amplitudes of the two used channels.

The output signals of each channel (Block Function 2 and Block Function 3) are then passed-through a high pass filter (Block function 6 and Block Function 5). The desired cut-off frequency of this filter has to be defined by the specifics of the application where this solution will be used. In a typical Motor Sport application this frequency could be 100 Hz or more (like 500 Hz).

The rectified signals from Block Function 6 and 5 are then compared to each other in Block Function 8. When both signals match each other (same values) then there will be a neutral Gain Control Signal (the gain of Block Function 4 will not change). In case the signals differ then the Gain Control signal will follow proportionally to the detected signal miss-match, in amplitude and polarity.

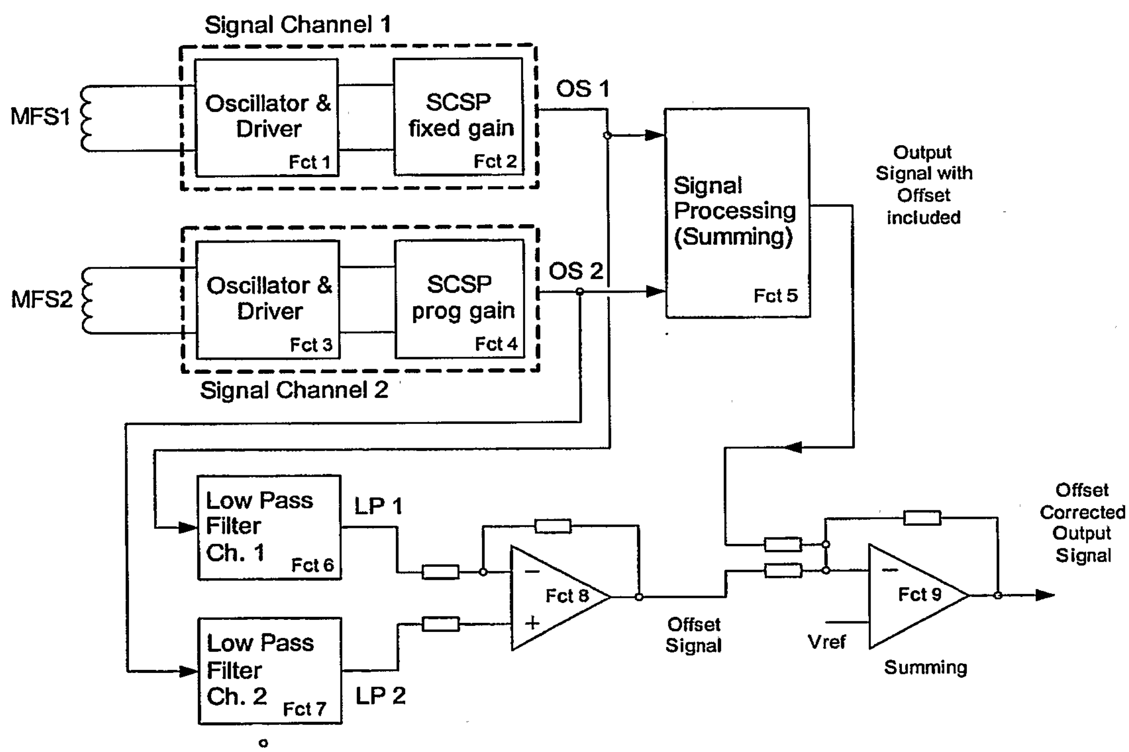
By changing the gain of Block Function 4 the system will be tuned to the point where both input channels (1 and 2) have overall matching gain specification (includes possible tolerances in the MFS devices).

In case there is no high frequency signal noise present (meaning that there is no signal present that is needed to detect gain differences in Channel 1 and 2) then the threshold detector Block Function 7 will disable the gain control function of Block Function 4. This solution prevents the AGM system from becoming instable.

The Invention 2: Automatic Offset Compensation (AOC)

In mobile applications where the magnetic principle based sensing device is surrounded by Ferro magnetic materials (example: engine block and gear box assembly), magnetic stray fields (like the Earth magnetic field) will be distorted. This will influence the systems ability to cancel-out formerly uniform (parallel) magnetic stray fields. Meaning the standard SCSP electronics will be unable to detect and eliminate the effects of EMF signal, for example.

In motor sport application where the car is driving around a closed-loop track, it is possible to detect the effect of the EMF (Earth Magnetic Field) caused signal offset by using low pass filters.



Drawing 2A: Block diagram of an active EMF canceling solution for applications where the EMF signal will be distorted.

Invention 1: Ability to actively detect and compensate the gain miss-matches in PCME multi-channel signal stages. This invention does not require any calibration and can be realized by using analog signal computation, or mixed signal computation, or full digital signal computation.

Invention 2: There is no need of using "mapping" solutions or an additional signal channel to detect and measure the true presents of the EMF signal. This solution

is using the already present signals and is extracting the information (influence of the EMF) through a very simple computation.

Target Applications

Applications where there is a high signal dynamic and a signal noise content > than 50 Hz :

- ☐ Motor Sport applications
- ☐ Engine Test Stands
- ☐ Impact and Impulse Power Tool Applications
- ☐ Marine Drive Shaft Application
- ☐ Avionic transmission control (Helicopter drive shafts)

In this report are a number of "new" acronyms used as otherwise some explanations and descriptions may be difficult to read. While the acronyms "ASIC", "IC", and "PCB" are already market standard definitions, there are many new terms that have been created in relation to the magnetostriction based NCT sensing technology.

Acronym	Description	Category
ASIC	Application Specific IC	Electronics
ASC	Automatic Slope Control	Sensor System
DF	Dual Field	Primary Sensor
EMF	Earth Magnetic Field	Test Criteria
FS	Full Scale	Test Criteria
Hot-Spotting	Sensitivity to nearby Ferro magnetic material	Specification
IC	Integrated Circuit	Electronics
MFS	Magnetic Field Sensor	Sensor Component
NCT	Non Contact Torque	Technology
PCB	Printed Circuit Board	Electronics
PCME	Pulse Current Modulated Encoding	Technology
POC	Proof-of-Concept	
RSU	Rotational Signal Uniformity	Specification
SCSP	Signal Conditioning & Signal Processing	Electronics
SF	Single Field	Primary Sensor
SH	Sensor Host	Primary Sensor
SPHC	Shaft Processing Holding Clamp	Processing Tool
SSU	Secondary Sensor Unit	Sensor Component

Sensor Host: Mechanic power transmitting shaft (for example produced out of Ferro magnetic material) that is the host (or carrier) of a Ferro magnetic sensor device.
Primary Sensor: Magnetically encoded section at the Sensor Host
Secondary Sensor: Magnetic pickup of the sensor information, emitted by the Primary Sensor

Sensor Aging: Unwanted signal slope reduction of the Primary Sensor due to physical mechanical overloads applied to the Primary Sensor, or due to other damages of the Primary Sensor.
"Total-Force" Technology: Sensing system technology that alerts the user when there are noticeable power losses in the torque sensing system

ASC = Automatic Slope Control

The Non-Contact PCME sensing technology requires that the Secondary Sensor is placed at a fixed distance in relation to the Primary Sensor. Explanation: The "radial" spacing between the Secondary Sensor module and the Sensor Host surface (or shaft surface) has to be kept constant.

The signal strength, emitted from the Primary Sensor, will degrade rapidly the further away the receiving Secondary Sensor module is placed. In case of an application where the entire sensor system is exposed to strong vibrations (example: Combustion engine, or impact power tools) it is possible that the PCME sensor output signal will show the effect of the system vibration in form of a signal amplitude modulation. The same could happen in an applications where changes in the ambient temperature has an effect on the mechanical position of the Secondary Sensor module in relation to the Primary Sensor location (example: different temperature expansions of materials used for the physical sensor design.

This issue can be controlled and dealt with by applying the proper care when designing the sensor system (using strong bearings, assuring that the temperature coefficient is matching for the different mechanical sensor modules / components). However, the circumstances may make it impossible to assure that the mechanical precision and stability required can be guarantied and therefore the "radial" spacing may vary during the use of the sensor system.

The here described invention provides a fully automatic compensation for the otherwise unwanted effects when the "radial" spacing is changing between the Secondary Sensor module and the Primary Sensor. This invention is called here: Automatic Slope Control or ASC.

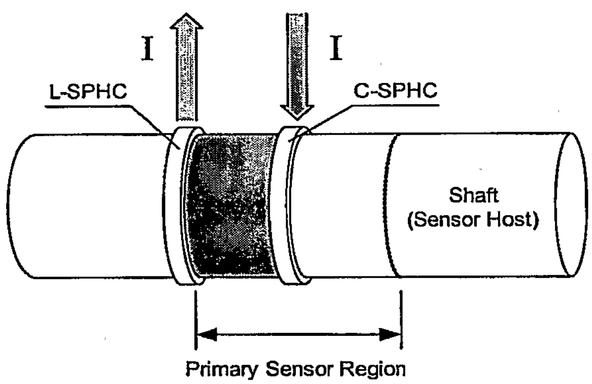
This invention is also capable to deal with the unwanted effects of sensor signal aging in case the sensor system has been exposed to mechanical overload. Explanation: In case the Sensor Host will be stressed to and beyond the point where "plastic" deformation of the Sensor Host is taking place, the PCME signal begins to weaken permanently (this phenomena is typical for many sensing technologies that rely on the principles of magnetostriction). This is here called "Sensor Aging").

The ASC technology is capable to compensate for the effects of sensor aging.

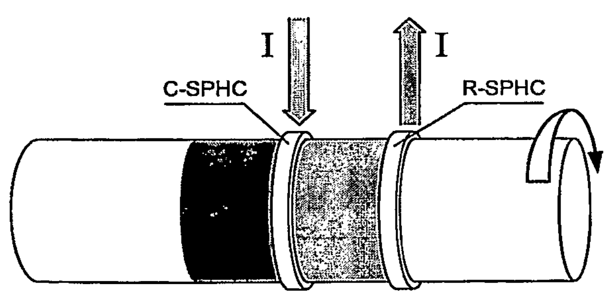
To achieve the ASC effect it is necessary to place a magnetic reference signal inside the Sensor Host. The Sensor Host will then carry the magnetic encoding of the PCME technology and a magnetic reference encoding in parallel to each other. It is the objective that the magnetic PCME encoding will continue to respond to the physical stresses applied to the Sensor Host, while the magnetic reference encoding will only react to the effects of sensor aging.

This ASC reference signal is placed in the SH during the PCME encoding process. Normally the PCME process is applied to the Sensor Host (SH) while the SH (or shaft) is in relaxed state (no mechanical stresses are applied to the SH). In case of the ASC technology, two PCME encoding processes will take place in succession (not in parallel) while one PCME process takes place in “relaxed” state, the other PCME process takes place while a known mechanical force (like torque) is applied to the SH.

By applying mechanical stress (like a torque force) to the SH during the PCME encoding process, the output signal of the final sensor system will have an electrical offset that is proportional to the applied mechanical stress.



Encoding Step 1: PCME process applied to SH while no mechanical forces are applied to SH

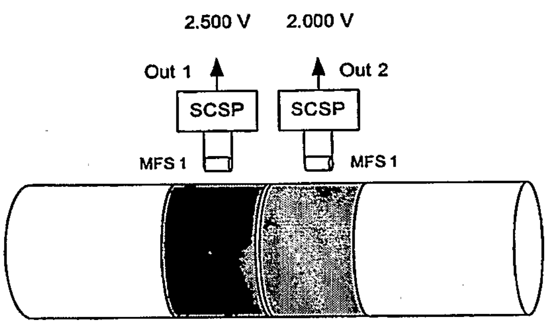


Encoding Step 2: PCME process applied to SH while a known mechanical forces is applied to SH

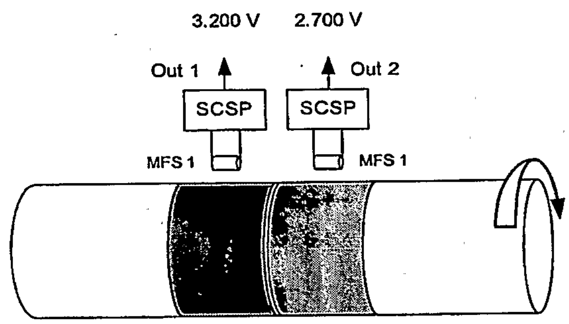
Drawing 1: A Dual PCME Field encoding is required to achieve the ASC effect. While one PCME encoding process happen while NO mechanical forces are applied to the SH, the other PCME encoding takes place while a known mechanical force (like torque) is applied to the SH. In principle there are no obligations in which order these process steps take place.

To recover the ASC reference signal, at least two MFS devices are needed that will form the Secondary Sensor Unit. It is important that the two MFS devices needed are mounted on the same frame to ensure that any change of spacing between the Secondary Sensor Unit and the Sensor Host (SH) will effect both MFS devices in exactly the same way.

It is also very important that the required SCSP (Signal Conditioning & Signal Processing) electronics for both channels (MFS1 and MFS2) are effected by the changes of supply voltages and ambient temperature changes in exactly the same quantitative way. Otherwise the ASC reference signal will not be reliable enough to achieve the desired performances.



PCME Sensor with ASC technology
when NO mechanical forces applied

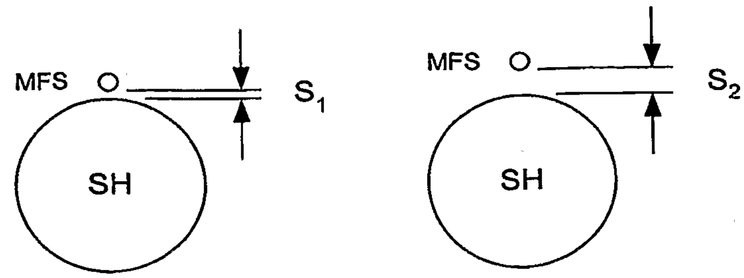


PCME Sensor with ASC technology
when specific torque force applied

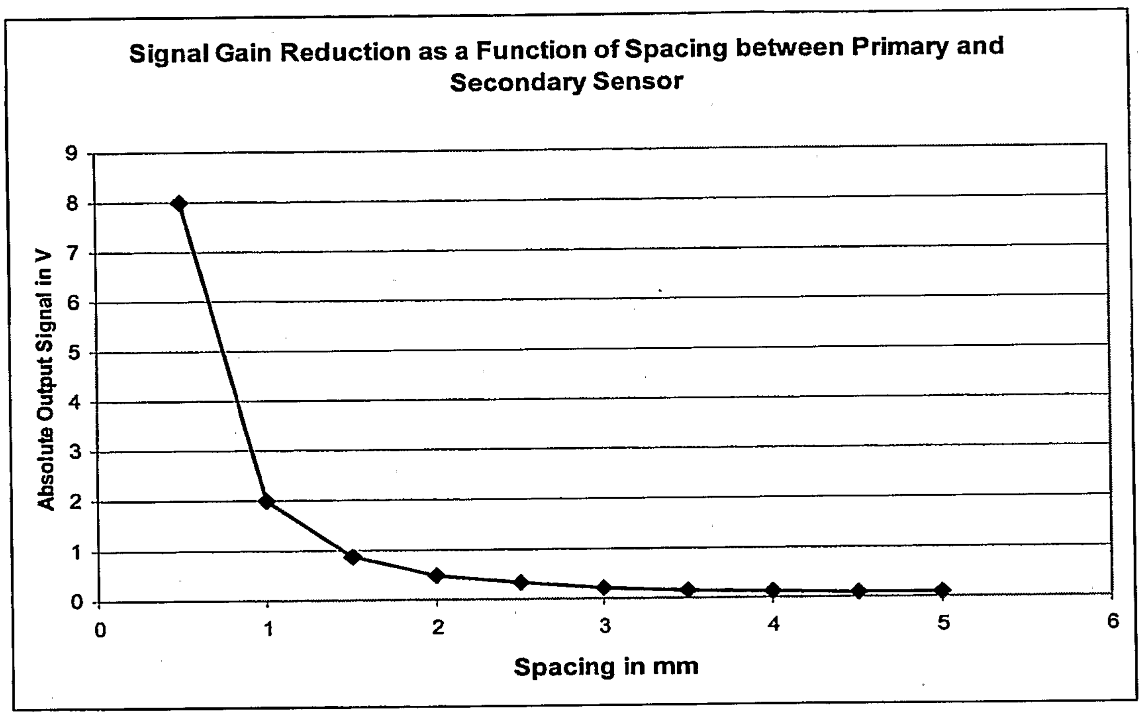
Drawing 2: Left picture: When the SH (Sensor Host or shaft) is in the relaxed state, the output signals from the two, independent working Secondary Sensor & SCSP (Signal Conditioning & Signal Processing) Channels (Output 1 and Output 2) reading the values: +2,500V and 2.000V. The difference between these two voltages is dependent on the applied mechanical force during the PCME SH processing, the gain setting of the SCSP electronics, and the spacing between the MFS and the SH-Shaft surface. In this example the difference is 2.500 V – 2.000 V = 0.500 V. This 0.500 V represent the ASC reference signal. Under normal condition the ASC reference signal remains constant.

Right picture: When applying a specific torque force to the SH the output voltages from both SCSP channels will change by the same amount. The change in output voltage is a proportional function of the applied mechanical force. However, the difference in the output Voltage from Channel 1 and Channel 2 remains constant (in this example: 3.200 V – 2.700 V = 0.500 V).

The signal increase from channel 1 (as a consequence of the applied torque force) is the difference between the two measurements: 3.300 V – 2.500 V = 0.700 V. The signal slope is a function of the spacing between the Primary Sensor (surface of the SH) to the Secondary Sensor (MFS device).

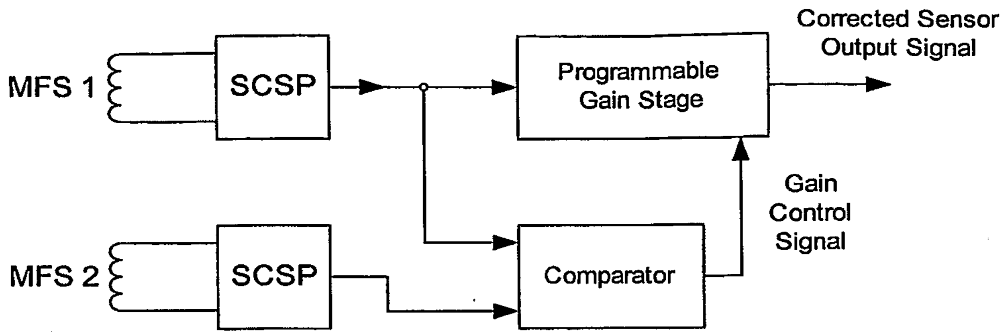


Drawing 3: As the spacing between the MFS (also called Secondary Sensor) is increasing (like from the values S_1 to the value S_2), the signal amplitude will drop.



Graph 1: With increasing spacing between the Secondary Sensor (MFS device) and the Primary Sensor (SH surface), the absolute signal amplitude will drop rapidly (function of the power to the spacing).

In the same way the signal amplitude will drop, so will the ASC signal. Note: The ASC signal is the difference between the output voltages from Channel 1 and Channel 2.



Drawing 3: Block diagram of the ASC electronics. In this simplified example the sensor signal, generated by the Secondary Sensor device: MFS 1, will be amplitude modulated in the module "Programmable Gain Stage". The difference between the signals MFS1 and MFS2 is processed in the module "Comparator". The output signal of the module "Comparator" is the "Gain Control Signal" of the Programmable Gain Stage. The larger the signal difference between MFS1 and MFS2, the lower the gain setting of the Programmable Gain Stage has to be. The lower the signal difference between MFS1 and MFS2, the higher the gain setting of the Programmable Gain Stage has to be.

With the increase of the gain setting, the Signal-to-Noise ratio will become poorer. Meaning that at some point the signal generated by MFS1 is so small that a high gain setting will amplify mainly the noise and consequently the resulting "Corrected Output Signal" is no longer of any use.

In this description "in-line" or "axial" positioned MFS devices have been used. However, this technology will work the same when using radial or tangentially placed MFS devises. Which way the MFS device has to be placed depends on what mechanical forces need to be measured and what type of mechanical force has been applied to the SH during one of the PCME encoding process.

The ASC technology is a true Non-Contact solution to detect and to correct changes of the PCME output signal amplitude caused by mechanical failures of the sensor system.

The ASC technology detects and corrects 100% the changes of the output signal amplitude, caused by sensor aging or by changes in the spacing between the Primary and Secondary Sensor. The space changing may be caused through mechanical damages in the sensor assembly, the effects of temperature (differences in physical expansion of the sensor material), or through mechanical vibrations in the sensor system.

The ASC technology will eliminate the need for sensors "gain"-setting calibration as the ASC reference signal gives a true representation of the sensor systems response to applied mechanical forces.

This technical solution does not require any more spacing on the SH. Meaning that the mechanical dimensions and the physical design of the "dual field" PCME sensor remains the same. There is no need to attaché any device or any substance on the SH and therefore the outstanding performances of the PCME sensor are not affected by the ASC technology.

The required electronics of the ASC solution is of low complexity and can be realized in analog signal processing technology or by using mixed signal (analog and digital) technology. When using the mixed signal approach there will be no need for any additional electronic component to implement the ASC technology. Meaning: no cost increase.

Benefits

The ASC technology can correct in real-time the output signal of a PCME sensor system. The output signal correction includes:

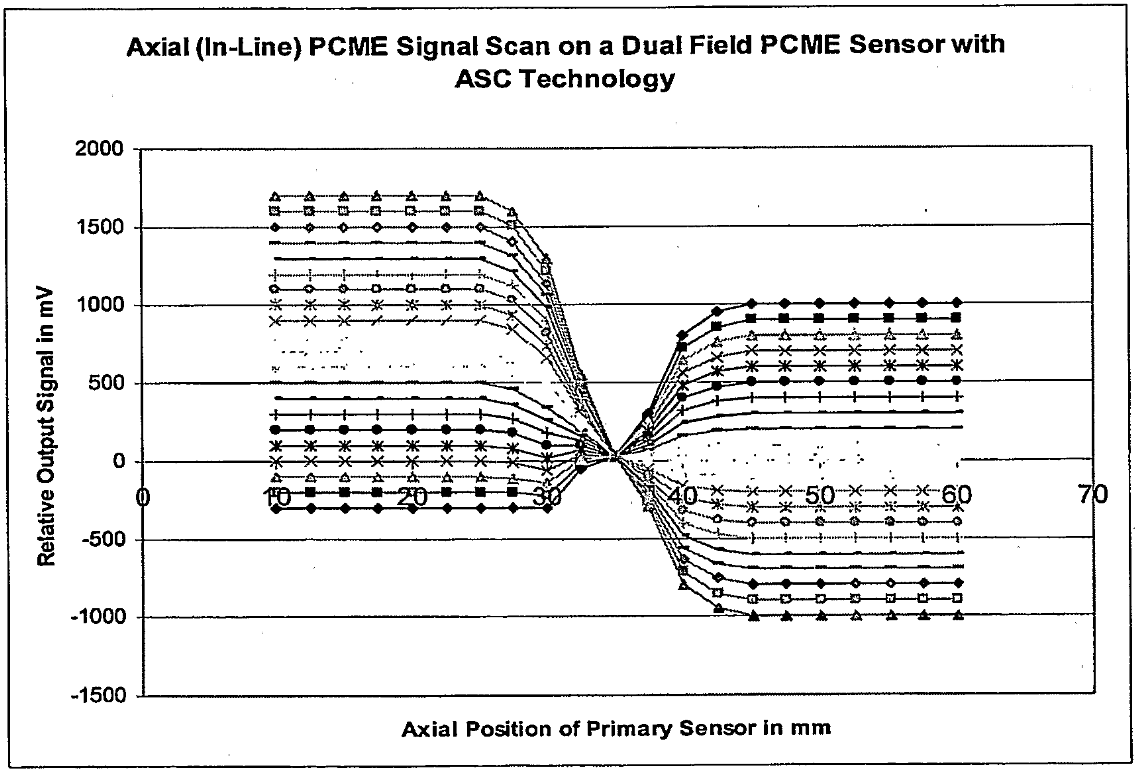
- ☐ Fully compensating the effects of unwanted changes in the spacing of the Secondary Sensor module during measurements
- ☐ Compensating the effects of senor aging, caused by applying a mechanical overload to the Primary Sensor device.
- ☐ Fully compensating the effects of gain changes in the SCSP electronics stages caused by the influence of ambient temperature changes.
- ☐ Eliminates the need for the sensors gain / slope calibration. The ASC reference signal can be used to define the actual sensor response to mechanical forces applied to the SH (or Primary Sensor).

The ASC technology may not add any costs in the actual sensor system and can be applied during the actual PCME encoding procedure.

Target Applications

The ASC technology is applicable to all PCME sensor designs where mechanical forces (like torque, axial forces, bending) or a position (rotational and linear) needs to be measured accurately. Particularly important is this technology for applications where there is a risk of mistreating the sensor system (detecting and compensating for the effects of applying a mechanical overload (resulting in Sensor Aging): Motor Sport, Industrial Drilling Applications, Impact and Impulse Power Tools.

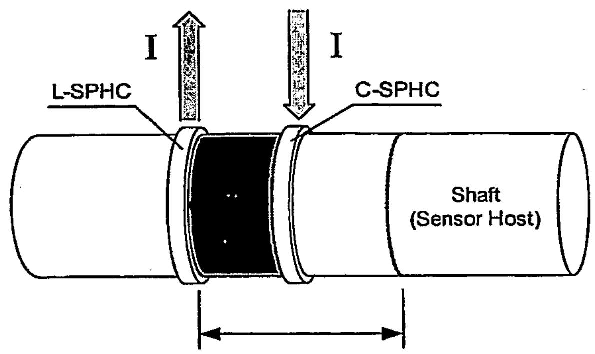
Background and Explanation
The drawing below shows the sensor system output signal as a function of the axial (in-line) location at the Primary Sensor region.



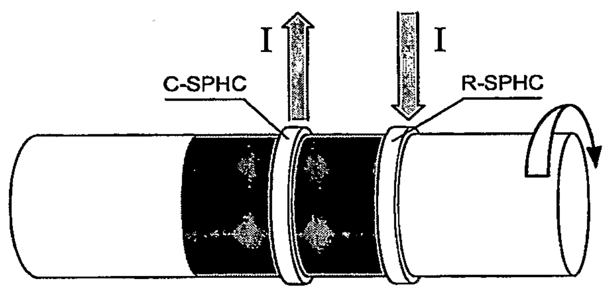
Graph 2: Sensor system output signal when moving one MFS device along the PCME encoded sections (Primary Sensor region). This graph has been generated from a Dual Field PCME sensor with reversed polarity encoding (process described in Drawing 1).

The reversed polarity encoding makes it simpler to cancel the effects of parallel / uniform magnetic stray fields, like the Earth Magnetic Field (EMF). This can be achieved by subtracting the output signals MFS1 from MFS2.

However, the ASC technology also works on a Dual Field PCME sensor with not reversed polarity encoding (see below).

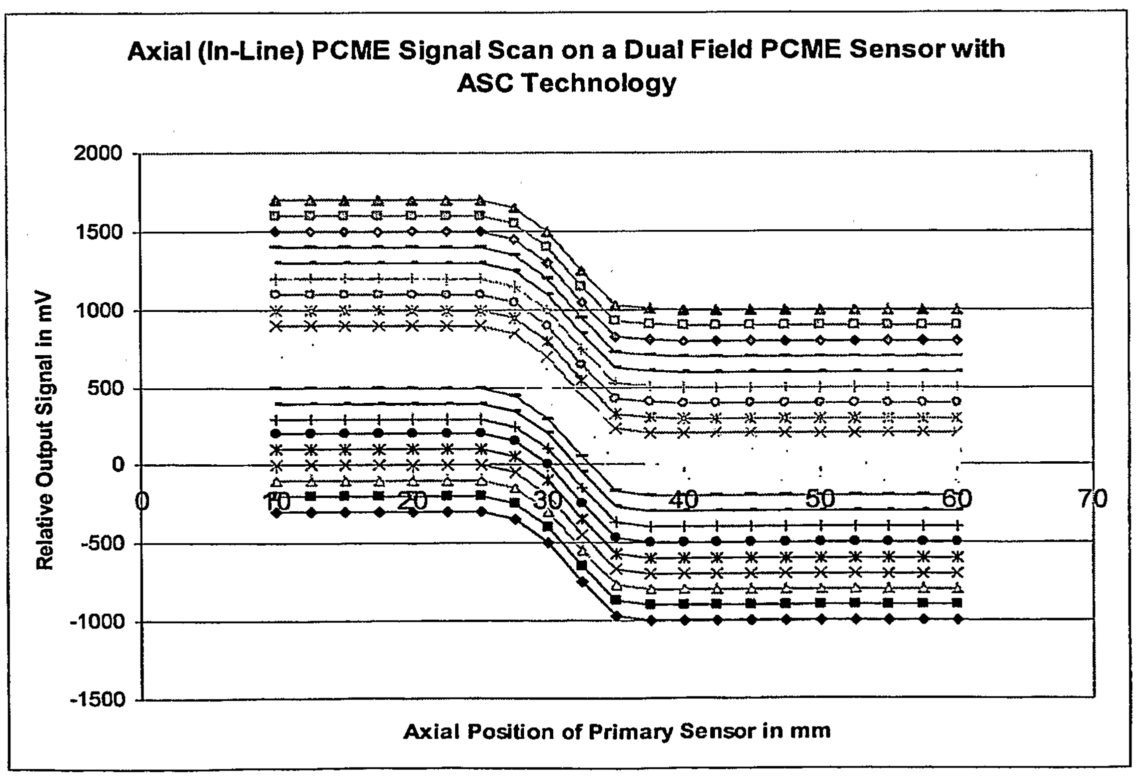


Encoding Step 1: PCME process applied to SH while no mechanical forces are applied to SH



Encoding Step 2: PCME process applied to SH while a known mechanical forces is applied to SH

Drawing 4: Dual Field, PCME processing, including ASC technology. The encoding polarity has not been reversed during the process.



Graph 3: Sensor System output signal when moving one MFS device axially along the Primary Sensor region. This graph comes from a Dual Field, not reversed polarity PCME sensor with ASC technology. The step function in the signal lines is caused by the PCME encoding while the sensor has been under mechanical stress (like torque).

Note that there is an area between the two parallel signal section that can not be used by the MFS devices as a signal pick-ups. In the drawing above the MFS 1 can be placed anywhere along the physical Primary Sensor positions: 10 mm till 25 mm. The MFS 2 can be placed anywhere from the axial position 36 mm to 60 mm. The area between the axial positions 25 mm to 36 mm is unusable for the ASC technology as the signal slope is changing (not stable).

Until now this report has described an ASC encoding process whereby only one PCME encoding step has been performed with physical load applied to the SH. It is possible to achieve a much larger signal step function when both PCME encoding steps are performed while a mechanical load is applied to the SH. However the mechanical load applied to the SH has to be in opposite direction to assure that the desired ASC reference signal can be generated.

Glossary

In this report are a number of "new" acronyms used as otherwise some explanations and descriptions may be difficult to read. While the acronyms "ASIC", "IC", and "PCB" are already market standard definitions, there are many new terms that have been created in relation to the magnetostriction based NCT sensing technology.

Acronym	**Description**	**Category**
ASIC	Application Specific IC	Electronics
ASC	Automatic Slope Control	Sensor System
DF	Dual Field	Primary Sensor
EMF	Earth Magnetic Field	Test Criteria
FS	Full Scale	Test Criteria
Hot-Spotting	Sensitivity to nearby Ferro magnetic material	Specification
IC	Integrated Circuit	Electronics
MFS	Magnetic Field Sensor	Sensor Component
NCT	Non Contact Torque	Technology
PCB	Printed Circuit Board	Electronics
PCME	Pulse Current Modulated Encoding	Technology
POC	Proof-of-Concept	
RSU	Rotational Signal Uniformity	Specification
SCSP	Signal Conditioning & Signal Processing	Electronics
SF	Single Field	Primary Sensor
SH	Sensor Host	Primary Sensor
SPHC	Shaft Processing Holding Clamp	Processing Tool
SSU	Secondary Sensor Unit	Sensor Component

Sensor Host: Mechanic power transmitting shaft (for example produced out of Ferro magnetic material) that is the host (or carrier) of a Ferro magnetic sensor device.
Primary Sensor: Magnetically encoded section at the Sensor Host
Secondary Sensor: Magnetic pickup of the sensor information, emitted by the Primary Sensor
Sensor Aging: Unwanted signal slope reduction of the Primary Sensor due to physical mechanical overloads applied to the Primary Sensor, or due to other damages of the Primary Sensor.

Patent Application: Wireless Sensor Power Supply and Signal read-out

Physical parameter sensor devices, like torque sensors, are often used as self-contained, stand alone sensor units in industrial applications or in industrial / automotive assembly line applications. One disadvantage of a traditional sensor device is that for the electrical intercommunication between the sensor and the external control system, electrical wires are needed.

For example, in a car-tire shop the torque sensor device will be used for quality control and safety inspections. During the process of tightening the log-nuts on each car wheel the worker needs to ensure that the correct torque is applied to the log-nut. The worker has to ensure that the bolts are not over-tightened or under-tightened. More-and-more the market and legislation demands that the actual torque applied to a bolt will be documented and this information needs to be stored for future references. To achieve this, the worker could use a hand held torque sensor device that will be attached to the front-end of the fastening tool (for example torque wrench, or a pneumatic / electrical powered fastening tool).

A torque sensor device that would be connected to the control system by wires is highly impractical. The operator (shop worker) of such tool is moving quickly around the car and from one car to the next so that it will be only a matter of time when the wiring will be ripped of by accident. Alternatively the operator has to work most carefully to avoid damaging the measurement system and therefore will be very time inefficient to finish the task at hand.

The here described solution focuses on the most challenging part: supplying electrical power to the sensor device "wire-less" and being able to use the same principle to read-out the sensors measurement results.

This solution is applicable to all types of sensor principles, and is particularly suitable when using the a magnetic based sensor principle.

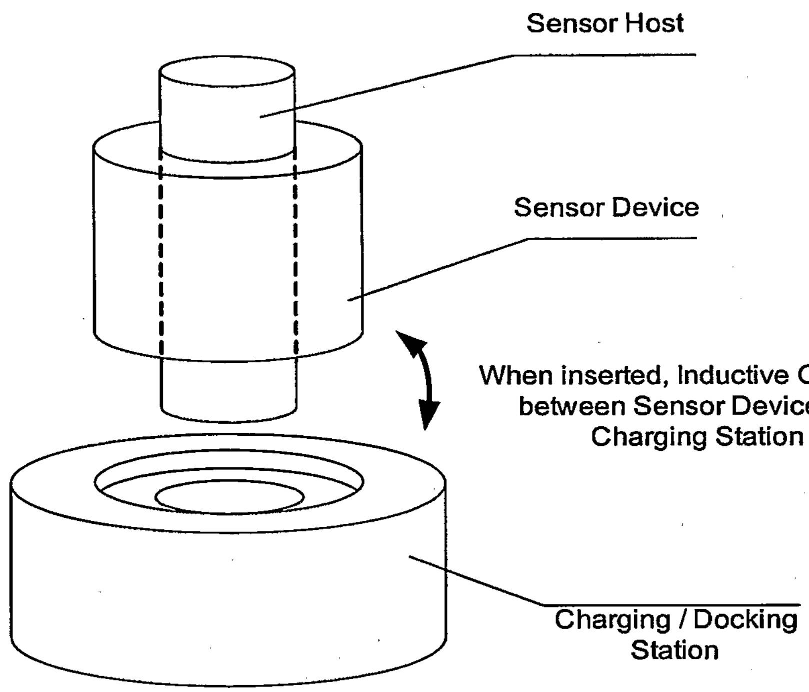
When not in use the sensor unit will rest in a specifically designed charging socket. Through inductive coupling methods the sensors on-board electrical storage device will be electrically charged.

In the case of PCME sensing technology the sensors current consumption is so low that a full charge of the on-board storage device will last from 8 hours (a full days of work) to several days.

When ever the sensor device is not in use it has to be placed back in the specific charging device. While resting in the charging device the connected control unit

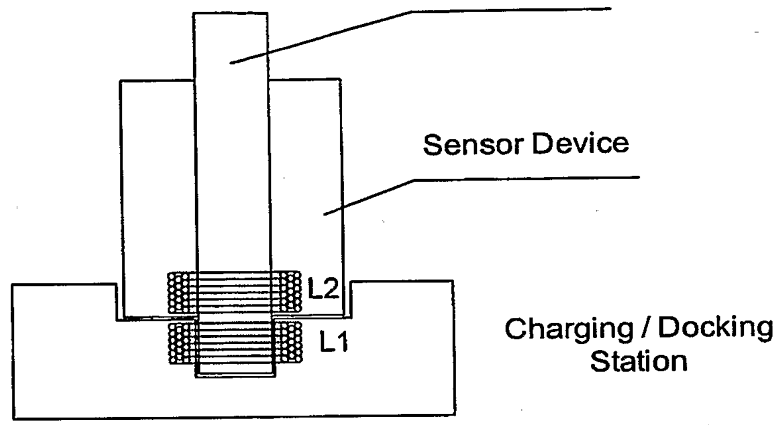
will read-out the measurement results and clear-out the sensors on-board memory.

The PCME magnetostriction based sensing principle relies on the reliability of the magnetic encoding of the mechanical power transmitting shaft (primary sensor). It is therefore critical that the chosen frequency of the inductive power coupling is high enough so that the magnetic encoding of the mechanical power transmitting shaft will not be damaged.

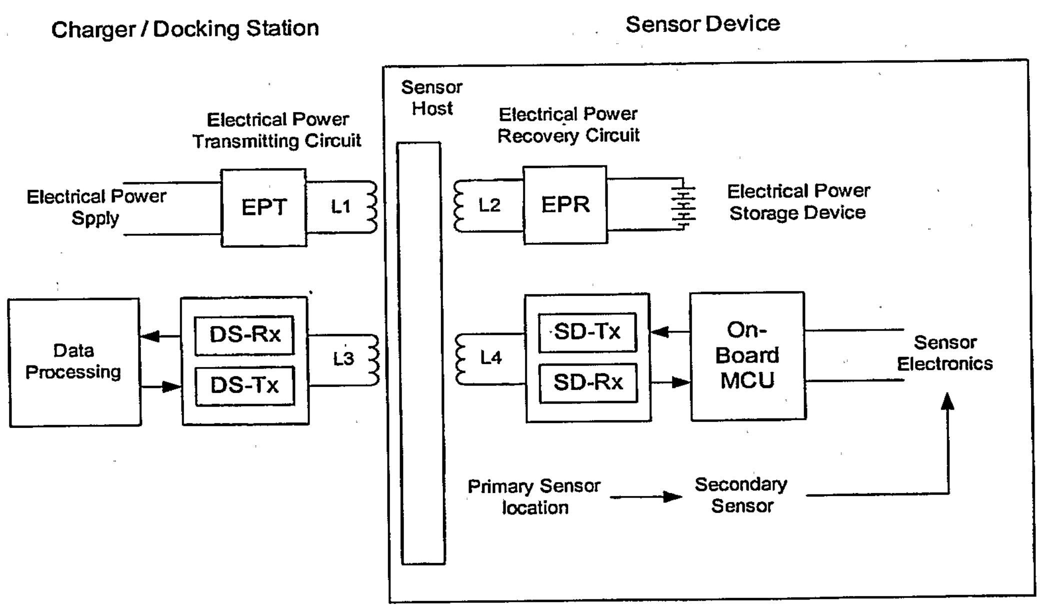


Drawing 1: Stand Alone sensor device (like a magnetic principle PCME sensor) that will be inserted into the Charging or Docking station. When inserted the magnetic inductive coupling takes place and allows electrical power transfer to the sensor devices and data communication from the sensor device to the docking station.

The optimal coupling frequency is dependent on the primary sensor shaft diameter (we assume that the primary sensor material is Ferro magnetic industrial steel). When the shaft diameter is less then 5 mm the coupling frequency has to be greater than 500 Hz to ensure no degrading of the primary sensors performances. The lower the inductive coupling frequency (when being below 500 Hz) the quicker the degrading of the sensor performance). At shaft diameters of 25 mm or more the inductive coupling frequency can drop to 250 Hz or even less.



Drawing 2: Built-in in the docking station is inductor L1 (Electrical Power transmitter and Sensor Signal Receiver), while built-in the sensor device is the inductor L2 (Electrical Power Receiver and Sensor Signal Transmitter).



Drawing 3: Block diagram of the functions: Wireless electrical power transmitter, and wireless data communication from and to the sensor device.

Although the inductive coupling devices for electrical power transmitting and data communication are separated, it is possible that these two functions can be placed together. In such a case only L1 and L2 are required.

Although the sensing principle is based on Ferro magnetic technology and therefore sensitive to externally applied strong magnetic fields (the primary sensor could be damaged or even erased), by choosing the right inductive coupling frequency it is possible to use the sensor host for four different functions at the same time:

- Transmitting of physical power (like torque)
- Being the host of the Primary Sensor
- Transmitter Medium for electrical power from the Docking Station into the Sensor Device
- Transmitting Medium for data communication between both, the sensor device and the docking station

The power transmission will happen at a frequency range of >250 Hz (preferable 500 Hz to 1 kHz) while the data communication between both devices (Docking station and Sensor Device) takes place at frequencies >>1 kHz (for example 10kHz or above).

In principle the data communication can happen at any frequency as long as the chosen frequency is not less than the electrical power transmitting frequency. However, by choosing a frequency that is identical to the electrical power transmitting frequency the data transfer rate will be relatively low. In addition the required signal separation circuit will be more complex than when choosing a much higher frequency for the data communication function.

The reason behind this is that the magnetic encoding of the PCME sensing technology is buried below the sensor host surface, deep enough so that the 500 Hz inductively coupled electrical power transmitting will not be able to reach and harm this permanently embedded magnetic field.

The higher the inductive coupling frequency the nearer the surface of the sensor host the magnetic field will travel.

Benefits

Wireless power transfer

    No cables that can fail (maintenances free, high MTBF)
    No hindrance to the operator as there are no wires in the way when using a sensor with this technology
    No batteries that need to be replaced

Wireless data communication between the devices

Sensor Device can be completely enclosed and sealed of from dirt or any liquid

    Lower manufacturing cost
    No weak spot in the sensor design as there is no need for any opening or access holes / panels

No radio interferences as the whole system works in a relative low end of the frequency spectrum

    Minimal load on the environment (no toxic material for batteries, low electro smog)

Low overall system complexity

    Low cost, simple design, high functionality

Background and Explanation

It is not desirable to have any physical opening (for the wiring of the power supply or data communication or for switches and data entry keys) in the housing of a

mechanical force sensing unit. Such openings potentially allow unwanted substances (oil, water, dirt, gases, ..) to enter the sensor unit when not sealed properly which will interfere with the sensor systems performance and expected life time. The physical "openings" of such a sensor will increase substantially the manufacturing costs of the sensor unit as well as the need for connection wires will limit and restrict the freedom of how and where the sensor unit can be use.

The electrical supply of a self-contained sensor device can be either generated by the sensor unit itself or can be provided by an on-board electrical power storage device.

On-Board Electrical Power Generating

In many applications the mechanical force transmitting shaft of the sensor unit will rotate during the measurements. In some applications the mechanical forces that need to be measured will change very regularly in repetitive patterns. Where these criteria's are fulfilled (either rotating shaft or regular changing mechanical force patterns) an on-board mechanical driven electrical power generating system can be used.

Even so the required electrical power is very small; any direct or indirect mechanical principle based power generating will generate "losses" in the sensor unit. The consequences in the measurement accuracy have to be fully understood before applying such a power supply technology.

Most practical is the generating of electrical power in sensor units where the sensor shaft is rotating in relation to the sensors housing. To minimize the possible impact on the measurement accuracy the power generator has to be placed at the sensors "input" or "supply" side of the mechanical force.

Solar-Light Power

As the overall sensors power consumption is very low. Therefore using electrical solar power cells can be used where light is available at the location where the sensor unit will be used.

Inductive Supply

An on-board, maintenance free, high capacity electrical storage device (like "Gold Caps") will provide enough electrical power for the desired sensors working period (like 8 hours for a full days work or 2 hours for a very specific tasks). The capacity will be recharged through electrical inductance coupling when the senor system is placed into a specific charging cradle.

The electro magnetic coupling frequency is high enough so that the primary sensor will not be accidentally demagnetized (frequency equal or higher than 250Hz).

Long-Life Electrical Power Storage On-Board

Today there are electrical power supply devices available that have an incredible high power density. As the overall electrical power consumption of a PCME sensor is very low, it is possible to design and construct a sensor device that has a life-time battery built in lasting several months.

In desired such a Long-Life battery can be made replaceable. But such a design will carry all the disadvantages described earlier.

A low-power consuming on-board micro controller can further preserve the electrical power consumption of the sensor device by detecting when the sensor is not in use and therefore put the sensor device in sleep mode or standby mode. Such a technique will prolog the on-board battery life-time to 2 years or even longer before the battery or the entire sensor needs replacing.

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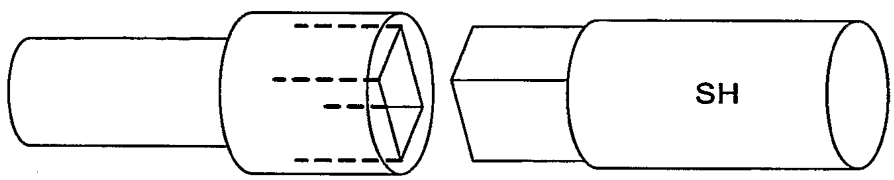
Primary Sensor: Magnetically encoded section at the Sensor Host
Secondary Sensor: Magnetic pickup of the sensor information, emitted by the Primary Sensor

Total-Force

The most critical factor to measure torque accurately is the alignment and mechanical interface of the torque sensor with the input and output shaft. When using a stand-alone torque sensor device in an industrial application, this sensing device has to be connected to the power input and power output shafts by using either standardized interface adapters or using a customized solution. Typical standard interface formats are male and female square ends, or round shaft ends with key-stone couplings.

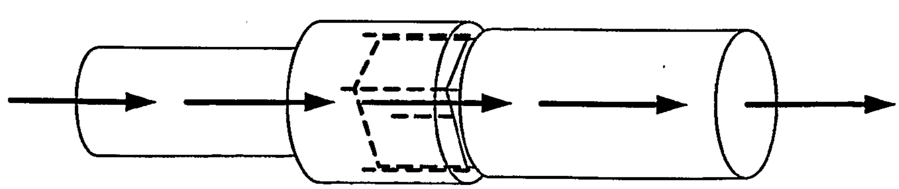
Mechanical Power Coupling using Square Adapter



Drawing 1: Typical mechanical coupling. In this example a mechanical square interface. The right part of this interface could be the Sensor Host (SH) of a PCME non-contact force sensor.

When using such a straight forward standard mechanical interface coupling the mechanical forces applied to the torque sensor will path through the sensing device as torque forces and as bending forces. The bending forces are caused by the non-ideal mechanical interface couplings on either side of the torque sensor. And it is the bending forces that will reduce the sensors accuracy by several percent. Even when using a high performing class 1 torque sensor the torque measurement result may be by 3% to >12% inaccurate because of the mechanical coupling issues.

It is the objective that the mechanical force (like torque) travels centric through the mechanical couplings



Mechanical Force (like Torque)

Drawing 2: When the two adapters have been inserted to each other it is the desire of the user that the mechanical force (like torque) is passing through the two couplings symmetrically (symbolically shown here through the center of the shafts and the couplings).

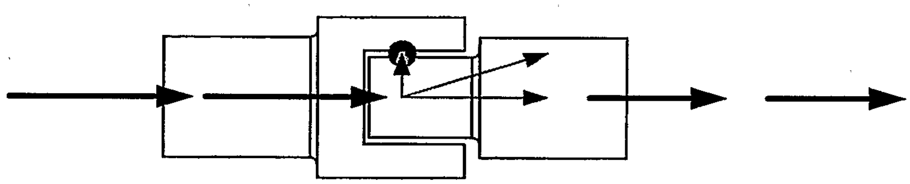
To ensure that the torque forces available from the power source (input shaft) are

recognized by the torque sensor to 100%, the torque forces have to enter and to leave the torque sensor device centric in relation to the measurement shaft. For example when using a round interface adapter with key-stone coupling, some of the mechanical forces (torque) will enter the input shaft in an angle, causing that the "torque" force becomes at least in part "bending" force. Although the entire mechanical forces will be transmitted through the sensor (depending on the used bearing support and sensor mounts), the sensor will NOT recognize all of these forces as torque.

Assumed Ideal Coupling

Real Non-Symmetric Mechanical Force Coupling

Drawing 3: In the ideal case it is assumed that the transmitted torque forces are coupled symmetrically (left picture, cross section view of the coupling) while in reality the torque forces are transmitted non-symmetrically through the "jamming" coupling (right picture, cross section view of the coupling).



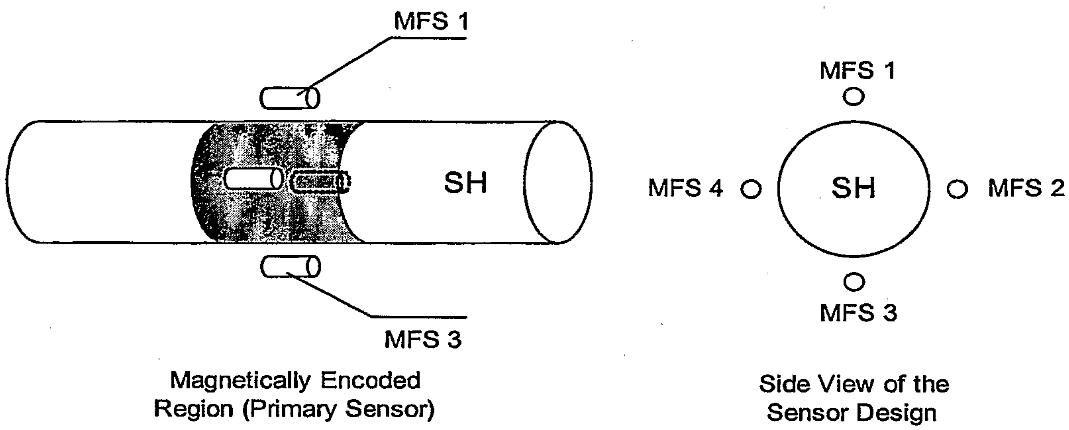
Transfer (Conversion) of Torque Force
into Torque + Bending Force

Drawing 4: Side view of the coupling: Depending on how the forces are transmitted through the mechanical square interface (does the mechanical coupling happen through 2, 3 or more physical connections inside the coupling?) the torque force entering from the left will be converted into a bending force and a torque force: The torque force has been divided into two different type of mechanical forces.

The here described invention, called "Total-Force" is capable of sensing and measuring ALL of the applied mechanical forces (torque, bending, sheering, pushing, pulling,) and therefore can compute all of the transmitted torque more accurately then most other industrial torque sensing devices. The signal output can be either an accurate torque reading or a warning to the user that the torque measurement setup will result in incorrect reading when not modified.

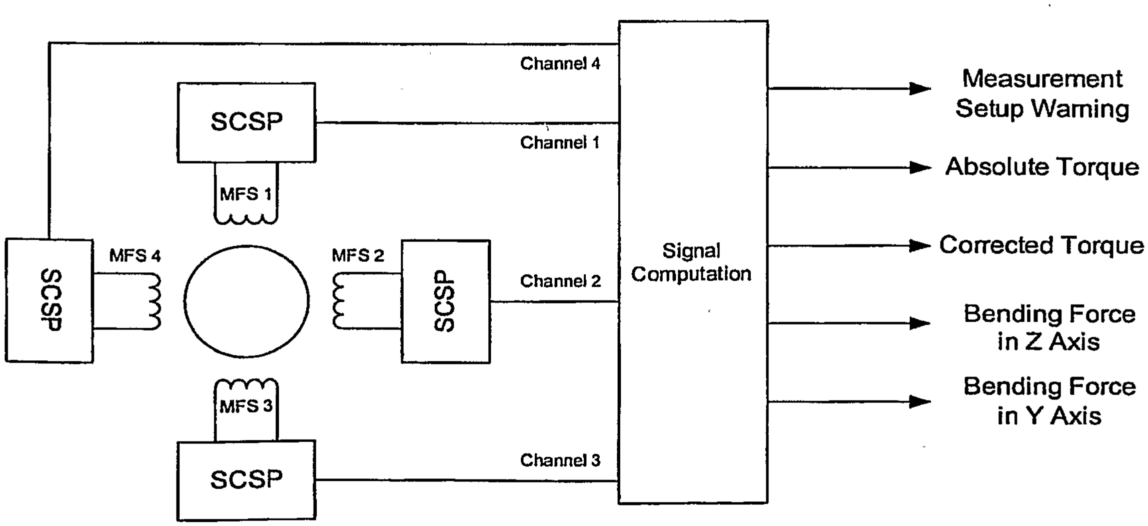
The "Total-Torque" force sensor is therefore an easy-to-use torque measure device, ideal in industrial application where cost, simplicity, and small space are crucial.

The "Total-Force" technology measures the mechanical bending stresses at the power transmitting sensor shaft at several different locations around the shaft. The measurement results are then computed by an on-board MCU. The user can then chose in what format he would like to process the information: Bending forces only, Torque forces only, axial mechanical forces (pushing or pulling) or All-Torque.



Drawing 5: In this example the Secondary Sensor Units (MFS) are placed at 90 deg intervals around the Primary Sensor region. Alternatively the same effect can be achieved by using only 3 sets of MFS devices and placing them at 120 deg to each other around the SH. In that case the signal computation is more complex.

Under ideal circumstances (when the mechanical force is transferred symmetrically through the couplings and the SH) only one Secondary Sensor Unit (one MFS set) is needed. To built a Total-Force sensor the bending forces have to be measured as well to be able identifying non-symmetrical force transfer. Therefore a number of MFS devises are placed symmetrically around the Primary Sensor.



Drawing 5: Block Diagram of Total Force systems electronics. The Signal Computation unit can be realised in analogue, mixed signal, or digital technology. The computation processes are simple and described below.

When calculating the average value out of the 4 signal sources ((Channel 1 + 2 + 3 + 4) / 4 = Torque) the resulting value is the absolute (true) transferred torque through the Primary Sensor Region (not corrected torque value).

When processing the signals from the Secondary Sensor devices that are placed opposite to each other (Channel 1 and Channel 3, or Channel 2 and Channel 4) the system can accurately define the present bending forces present in the Primary Sensor region. The calculated bending forces are passed-on to the signal outputs: Bending Force in Z axis, and Bending Force in Y axis.

When detecting that the calculated bending forces exceed a certain percentage of the calculated torque forces then a warning signal is made available (Signal Output: "Measurement Setup Warning"), telling the user that the torque reading-error exceeds a predefined value. In this case the user has the option to make corrections to the coupling setup in order to reduce this torque measurement error.

In case the exact dimensions and the exact physical behavior of the used mechanical couplings are known then the Signal Computation unit can correct the torque reading and convert back the unwanted bending forces reading into torque forces reading. The resulting value, "Corrected Torque" is the passed-on to the according signal output. Note: The mechanical sensor system setup has to be fully understood before the "Corrected Torque" signal can be used.

Lowest computational requirements are needed when the mechanical stresses are detected and measured at every 90 deg around the sensor shaft. However, the same measurement results can be achieved when using three sensors, placed at 0 deg, 120 deg, and 240 deg around the shaft. In this case the computational requirements are considerably higher.

The "True Torque" sensing technology allows to identify torque losses or power losses inside a stand-alone force sensor device. The torque losses are caused through poor mechanical coupling as used in many industrial applications.

The "True Torque" technology does not require any more spacing in an existing non-contact sensor system, like a PCME sensor device. Nor are any changes required to the Primary Sensor region (or SH).

The "True-Torque" technology operates by using an existing PCME encoded shaft (no changes in the SH processing are needed), therefore no cost adder.

The "True Torque" technology operates in real time and does not slow down any measurement operation.

The industrial user, who is not very familiar about how to setup correctly a torque measurement system will benefit greatly by the "Measurement Setup Warning" signal. Until now the user had little or no idea that the torque measurements he did are incorrect, even so he was using a high precision and costly torque sensor system.

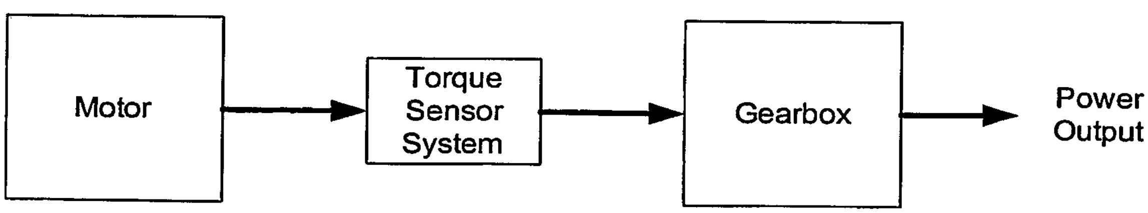
The "True Torque" technology allows the user to purchase "low budget" torque sensor systems as he is now able to achieve much higher measurement accuracy (better than one percent) with this technology than when using high precision torque sensors in a poor mechanical setup. Without "True Torque", in a typical industrial torque-sensor system setup, the achievable measurement accuracy may be only 5% or worse.

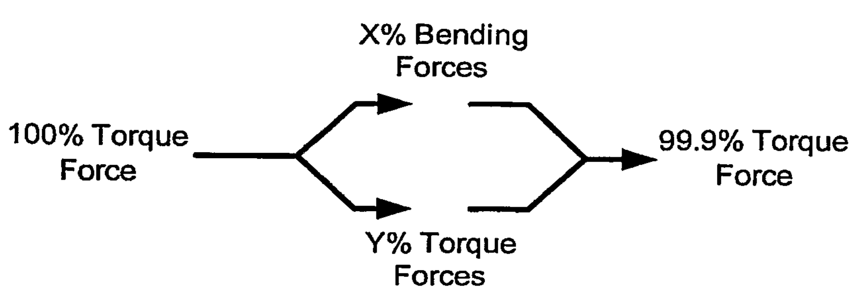
When ever a stand-alone mechanical force sensor device will be used and integrated into a measurement setup, like:

- ☐ Industrial calibration and maintenance applications (Gearbox testing, Motor testing, power transition testing).
- ☐ Laboratory applications (calibrations and measurements)
- ☐ Motor Test stand applications
- ☐ Automotive power transmissions
- ☐ Power tool calibration
- ☐ Power tool torque adapter

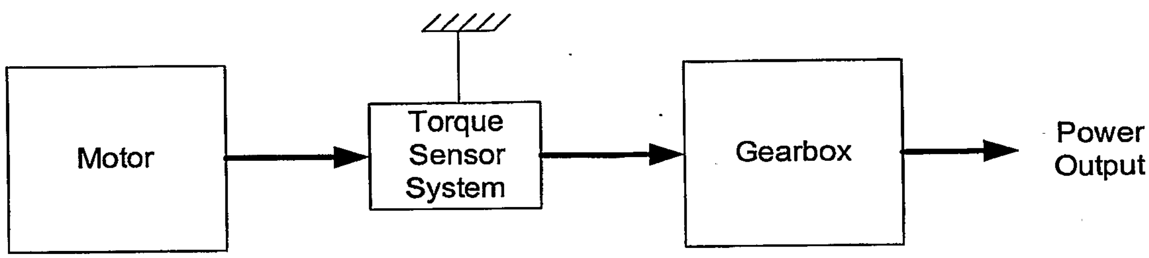
Background and Explanation

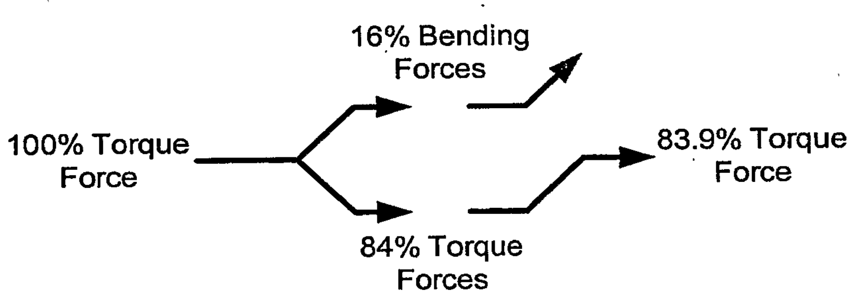
In an ideal system setup (typical example shown below) the torque forces applied to a sensor system, and the torque forces that are available at the sensor system are almost identical. In reality there are always losses of some kind, even so these losses might be very small.





Drawing 6: This picture demonstrates how torque forces coming from a power source, like a motor, may be split into torque-forces and bending-forces when using a separate (stand-alone) torque sensor system. The reason for this unwanted force conversion are none-ideal mechanical couplings at the sensor input and the sensor output. However, in this example almost all of the mechanical forces that are passed through the sensor system turn into torque forces again and very little power has been lost.





Drawing 7: In applications where the "stand-alone" torque sensing system is mechanically fixed to a separate fixture, the risk is very high that some or all of the converted forces (into bending forces) will be lost. Meaning that the Gearbox receives noticeably less power then the motor has provided.

The "Total Force" technology will make the user aware about this power loss so that he can correct coupling problems.

In this report are a number of "new" acronyms used as otherwise some explanations and descriptions may be difficult to read. While the acronyms "ASIC", "IC", and "PCB" are already market standard definitions, there are many new terms that have been created in relation to the magnetostriction based NCT sensing technology.

Acronym	Description	Category
ASIC	Application Specific IC	Electronics
ASC	Automatic Slope Control	Sensor System
DF	Dual Field	Primary Sensor
EMF	Earth Magnetic Field	Test Criteria
FS	Full Scale	Test Criteria
Hot-Spotting	Sensitivity to nearby Ferro magnetic material	Specification
IC	Integrated Circuit	Electronics
MFS	Magnetic Field Sensor	Sensor Component

NCT	Non Contact Torque	Technology
PCB	Printed Circuit Board	Electronics
PCME	Pulse Current Modulated Encoding	Technology
POC	Proof-of-Concept	
RSU	Rotational Signal Uniformity	Specification
SCSP	Signal Conditioning & Signal Processing	Electronics
SF	Single Field	Primary Sensor
SH	Sensor Host	Primary Sensor
SPHC	Shaft Processing Holding Clamp	Processing Tool
SSU	Secondary Sensor Unit	Sensor Component

Sensor Host: Mechanic power transmitting shaft (for example produced out of Ferro magnetic material) that is the host (or carrier) of a Ferro magnetic sensor device.
Primary Sensor: Magnetically encoded section at the Sensor Host
Secondary Sensor: Magnetic pickup of the sensor information, emitted by the Primary Sensor
Sensor Aging: Unwanted signal slope reduction of the Primary Sensor due to physical mechanical overloads applied to the Primary Sensor, or due to other damages of the Primary Sensor.
"Total-Force" Technology: Sensing system technology that alerts the user when there are noticeable power losses in the torque sensing system

60/533 276 2. August 2004

NCTENGINEERING GMBH

What is claimed is:

1. Torque sensor, comprising:

a first sensor element with a magnetically encoded region; and

a second sensor element with at least one magnetic field detector;

wherein the first sensor element has a surface;

wherein, in a direction essentially perpendicular to the surface of the first sensor element, the magnetically encoded region of the first sensor element has a magnetic field structure such that there is a first magnetic flow in a first direction and a second magnetic flow in a second direction;

wherein the first direction is opposite to the second direction;

wherein the first sensor element is a shaft;

wherein in a cross-sectional view of the shaft, there is a first circular magnetic flow having the first direction and a first radius and a second circular magnetic flow having the second direction and a second radius;

wherein the first radius is larger than the second radius;

wherein a sensor electronic is provided;

wherein the sensor electronic implements an automatic slope control;

wherein a wireless sensor power supply and signal read-out is provided; and

wherein a total force measurement element is provided.

2. Method of magnetizing an metallic body element, the method comprising:

applying at least two current pulses to the metallic body element such that in a direction essentially perpendicular to a surface of the metallic body element, a

magnetic field structure is generated such that there is a first magnetic flow in a first direction and a second magnetic flow in a second direction;

wherein the first direction is opposite to the second direction;

wherein, in a time versus current diagram, each of the at least two current pulses has a fast raising edge which is essentially vertical and has a slow falling edge;

wherein a sensor electronic is provided;

wherein the sensor electronic implements an automatic slope control;

wherein a wireless sensor power supply and signal read-out is performed; and

wherein a total force measurement performed.

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February 08, 2005

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FILING DATE: ***December 30, 2003***

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Serial No.	:	**To Be Assigned**
Filing Date	:	**December 30, 2003**
For	:	**PCM-ENCODED TORQUE SENSING TECHNOLOGY**

Commissioner for Patents
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I hereby certify that this correspondence is being deposited with the United States Postal Service "Express Mail Post Office to Addressee" service under 37 CFR 1.10 on the date indicated above and is addressed to: Commissioner for Patents, P.O. Box 1450, Alexandria, VA. 22313-1450

name: Oleg F. Kaplun (Reg. No. 45,559)

Signature

PROVISIONAL PATENT APPLICATION TRANSMITTAL

SIRS:

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR 1.53(c).

Inventor(s) and Residence(s) (city and either state or foreign country):

Lutz MAY
Wolfratshauser Str. 23a
D-82578 Geretsried-Gelting
Germany
Citizenship: Germany

Inventor encloses:

1. **38** sheets of Specification and
2. Return postcard.

Please charge the Deposit Account of **Fay Kaplun & Marcin, LLP, No. 50-1492** in the amount of **$160.00** for the filing fee.

The Commissioner is hereby authorized to charge the payment of any additional fees associated with this communication or arising during the pendency of this application, to the Deposit Account of **Fay Kaplun & Marcin, LLP No. 50-1492**.

Date: December 30, 2003

By: ______________________
Oleg F. Kaplun (Reg. No. 45,559)

Fay Kaplun & Marcin, LLP
150 Broadway, Suite 702
New York, NY 10038
Tel: 212-619-6000
Fax: 212-619-0276

US Provisional Patent Application

PCM-Encoded Torque Sensing Technology

Field of the Invention

The magnetic principle based mechanical-stress sensing technology allows to design and to produce a wide range of "physical-parameter-sensors" (like Force Sensing, Torque Sensing, and Material Diagnostic Analysis) that can be applied where Ferro-Magnetic materials are used. The most common technologies used to build "magnetic-principle-based" sensors are: Inductive differential displacement measurement (requires torsion shaft), Measuring the changes of the materials permeability, and measuring the magnetostriction effects.

Over the last 20 years a number of different companies have developed their own and very specific solution in how to design and how to produce a magnetic principle based torque sensor (i.e. ABB, FAST, Frauenhofer Institute, FT, Kubota, MDI, NCTE, RM, Siemens, and others). These technologies are at various development stages and differ in "how-it-works", the achievable performance, the systems reliability, and the manufacturing / system cost.

Some of these technologies require that mechanical changes are made to the shaft where torque should be measured (chevrons), or rely on the mechanical torsion effect (require a long shaft that twists under torque), or that something will be attached to the shaft itself (press-fitting a ring of certain properties to the shaft surface,), or coating of the shaft surface with a special substance. No-one has yet mastered a high-volume manufacturing process that can be applied to (almost) any shaft size, achieving tight performance tolerances, and is not based on already existing technology patents.

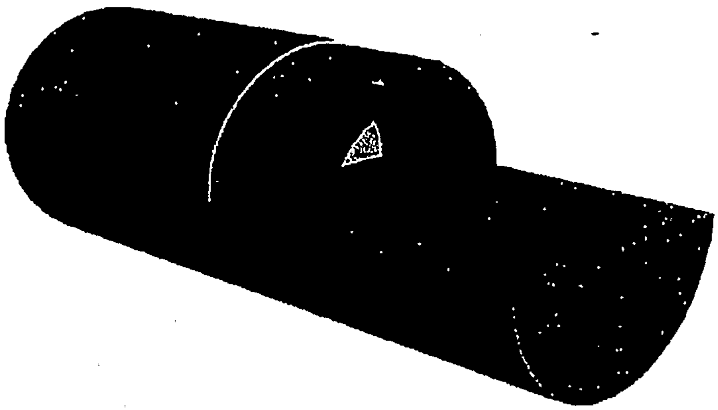
Summary of the Invention and Exemplary embodiments of the present invention

In the following, exemplary embodiments of the present invention relating to a magnetostriction principle based ***Non-Contact-Torque*** (NCT) Sensing Technology are described that offer to the user a whole host of new features and improved performances, previously not available. This technology enables the realization of a fully-integrated (small in space), real-time (high signal bandwidth) torque measurement, which is reliable and can be produced at an affordable cost, at any desired quantities. This technology is called: ***PCME*** (for Pulse-Current-Modulated Encoding) or Magnetostriction Transversal Torque Sensor.

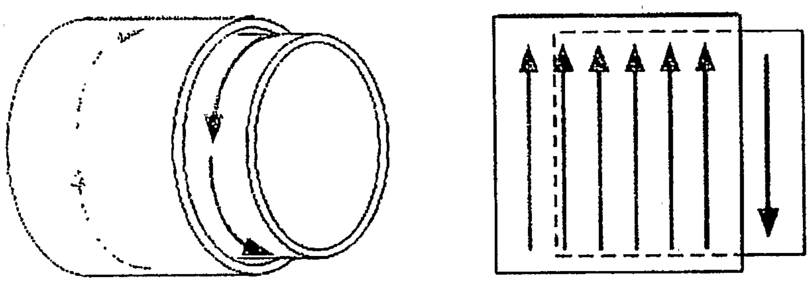
The PCME technology can be applied to the shaft without making any mechanical changes to the shaft, or without attaching anything to the shaft. Most important, the PCME technology can be applied to any shaft diameter (most other technologies have here a limitation) and does not need to rotate / spin the shaft during the encoding process (very simple and low-cost manufacturing process) which makes this technology very applicable for high-volume application.

Magnetic Field Structure (Sensor Principle)

The sensor life-time depends on a "closed-loop" magnetic field design. The PCME technology is based on two magnetic field structures, stored above each other, and running in opposite directions. When no torque stress is applied to the shaft (also called Sensor Host, or SH) then the SH will act magnetically neutral (no magnetic field can be sensed at the outside of the SH).

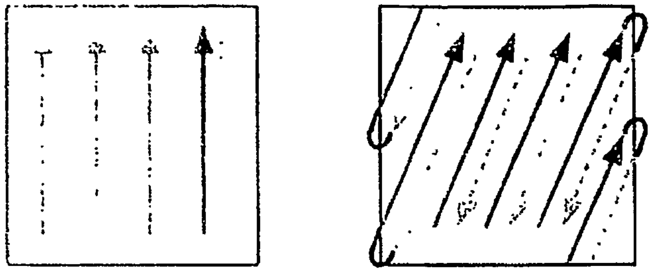


Picture: The picture shows an exemplary embodiment of the present invention where two magnetic fields are stored in the SH and running in endless circles. The outer field runs in one direction, while the inner field runs in the opposite direction.



Drawing: The PCME sensing technology uses two Counter-Circular magnetic fiel d loops that are stored on top of each other (Picky-Back mode).

When mechanical stress (like torque) is applied at both ends of the PCME magnetized SH (Sensor Host, or Shaft) then the magnetic flux lines of both magnetic structures (or loops) will tilt in proportion to the applied torque.

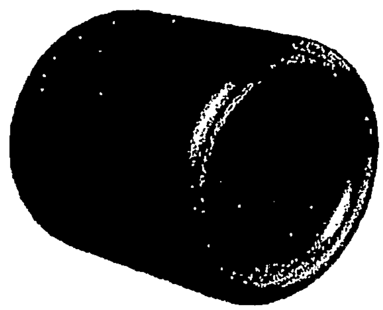


Drawing: When no mechanical stresses are applied to the SH the magnetic flux lines are running in its original path. When mechanical tresses are applied the magnetic flux lines tilt in proportion to the applied stress (like torque).

Depending on the applied torque direction (clockwise or anti-clockwise, in relation to the SH) the magnetic flux lines will either tilt to the right or tilt to the left. Where the magnetic flux lines reach the boundary of the magnetically encoded region, the magnetic flux lines from the upper layer will join-up with the magnetic flux lines from the lower layer and visa-versa. This will then form a perfectly controlled toroidal shape.

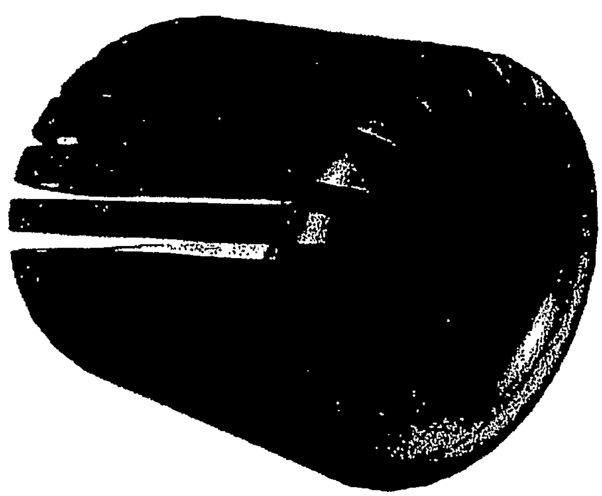
The benefits of such a magnetic structure are:

- ☐ Reduced (almost eliminated) parasitic magnetic field structures when mechanical stress is applied to the SH (this will result in better RSU performances).
- ☐ Higher Sensor-Output Signal-Slope as there are two "active" layers that compliment each other when generating a mechanical stress related signal. Explanation: When using a single-layer sensor design, the "tilted" magnetic flux lines that exit at the encoding region boundary have to create a "return passage" from one boundary side to the other. This effort effects how much signal is available to be sensed and measured outside of the SH with the secondary sensor unit.
- ☐ There are almost no limitations on the SH (shaft) dimensions where the PCME technology will be applied to. The dual layered magnetic field structure can be adapted to any solid or hollow shaft dimensions.
- ☐ The physical dimensions and sensor performances are in a very wide range programmable and therefore can be tailored to the targeted application.
- ☐ This sensor design allows to measure mechanical stresses coming from all three dimensions axis, including in-line forces applied to the shaft (applicable as a load-cell). Explanation: Earlier magnetostriction sensor designs (for example from FAST Technology) have been limited to be sensitive in 2 dimensional axis only, and could not measure in-line forces.



Picture: When torque is applied to the SH, the magnetic flux lines from both Counter-Circular magnetic loops are connecting to each other at the sensor region boundaries.

When mechanical torque stress is applied to the SH then the magnetic field will no longer run around in circles but tilt slightly in proportion to the applied torque stress. This will cause the magnetic field lines from one layer to connect to the magnetic field lines in the other layer, and with this form a toroidal shape.



Picture: An exaggerated presentation of how the magnetic flux line will form an angled toroidal structure when high levels of torque are applied to the SH.

Features and Benefits of the PCM-Encoding (PCME) Process

The magnetostriction NCT sensing technology from NCTE according to the present invention offers high performance torque sensing features like:

- ☐ No mechanical changes required on the Sensor Host (already existing shafts can be used as they are)
- ☐ Nothing will be attached to the Sensor Host (therefore nothing can fall off or change over the shaft-lifetime = high MTBF)
- ☐ During measurement the SH can rotate at any desired speed (no limitations on rpm)
- ☐ Very good RSU (Rotational Signal Uniformity) performances
- ☐ Excellent measurement linearity (up to 0.01% of FS)
- ☐ High measurement repeatability
- ☐ Very high signal resolution (better than 14 bit)
- ☐ Very high signal bandwidth (better than 10 kHz)

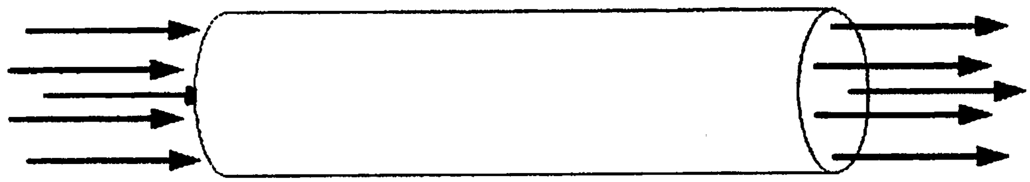
Depending on the chosen type of magnetostriction sensing technology, and the chosen physical sensor design, the mechanical power transmitting shaft (also called "Sensor Host" or in short "SH") can be used "as is" without making any mechanical changes to it or without attaching anything to the shaft. This is then called a "true" Non-Contact-Torque measurement principle allowing the shaft to rotate freely at any desired speed in both directions.

The here described PCM-Encoding (PCME) manufacturing process according to an exemplary embodiment of the present invention provides additional features no other magnetostriction technology can offer (*Uniqueness of this technology*):

- ☐ More then three times signal strength in comparison to alternative magnetostriction encoding processes (like the "RS" process from FAST).
- ☐ Easy and simple shaft loading process (high manufacturing through-putt).
- ☐ No moving components during magnetic encoding process (low complexity manufacturing equipment = high MTBF, and lower cost).
- ☐ Process allows NCT sensor to be "fine-tuning" to achieve target accuracy of a fraction of one percent.
- ☐ Manufacturing process allows shaft "pre-processing" and "post-processing" in the same process cycle (high manufacturing through-putt).
- ☐ Sensing technology and manufacturing process is ratio-metric and therefore is applicable to all shaft or tube diameters.
- ☐ The PCM-Encoding process can be applied while the SH is already assembled (depending on accessibility) (maintenance friendly).
- ☐ Final sensor is insensitive to axial shaft movements (the actual allowable axial shaft movement depends on the physical "length" of the magnetically encoded region).
- ☐ Magnetically encoded SH remains neutral and has little to non magnetic field when no forces (like torque) are applied to the SH.
- ☐ Sensitive to mechanical forces in all three dimensional axis.

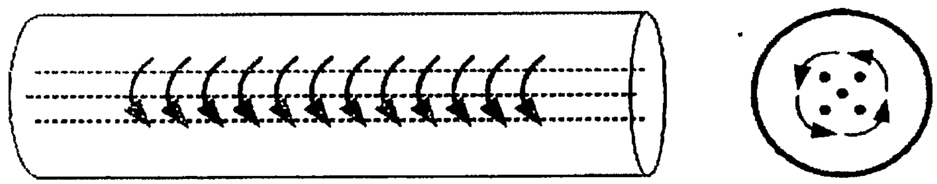
Magnetic Flux Distribution in the SH

The PCME processing technology is based on using electrical currents, passing through the SH (Sensor Host or Shaft) to achieve the desired, permanent magnetic encoding of the Ferro-magnetic material. To achieve the desired sensor performance and features a very specific and well controlled electrical current is required. Early experiments that used DC currents failed because of luck of understanding how small amounts and large amounts of DC electric current are traveling through a conductor (in this case the "conductor" is the mechanical power transmitting shaft, also called Sensor Host or in short "SH").



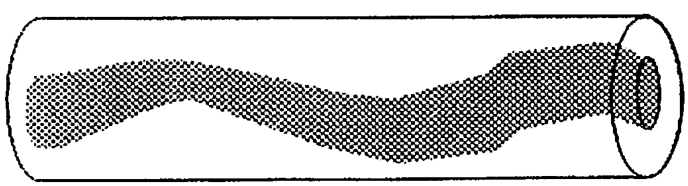
Drawing: Assumed electrical current density in a conductor

It is widely assumed that the electric current density in a conductor is evenly distributed over the entire cross-section of the conductor when an electric current (DC) passes through the conductor.



Drawing: Small electrical current forming magnetic field that ties current path in a conductor.

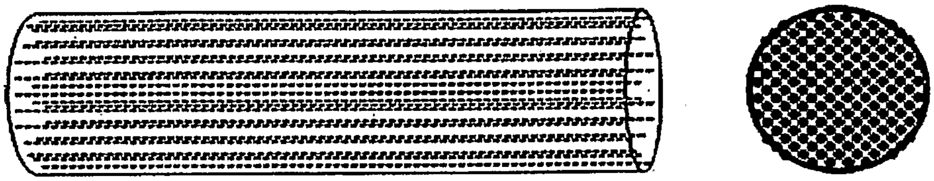
It is our experience that when a small amount of electrical current (DC) is passing through the conductor that the current density is highest at the center of the conductor. The two main reasons for this are: The electric current passing through a conductor generates a magnetic field that is tying together the current path in the center of the conductor, and the impedance is the lowest in the center of the conductor.



Drawing: Typical flow of small electrical currents in a conductor

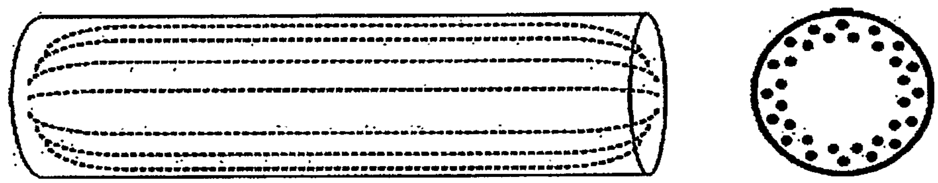
In reality, however, the electric current may not flow in a "straight" line from one connection pole to the other (similar to the shape of electric lightening in the sky).

At a certain level of electric current the generated magnetic field is large enough to cause a permanent magnetization of the Ferro-magnetic shaft material. As the electric current is flowing near or at the center of the SH, the permanently stored magnetic field will reside at the same location: near or at the center of the SH. When now applying mechanical torque to the shaft then shaft internally stored magnetic field will respond by tilting its magnetic flux path in accordance to the applied mechanical force. As the permanently stored magnetic field lies deep below the shaft surface the measurable effects are very small, not uniform and therefore not sufficient to build a reliable NCT sensor system.



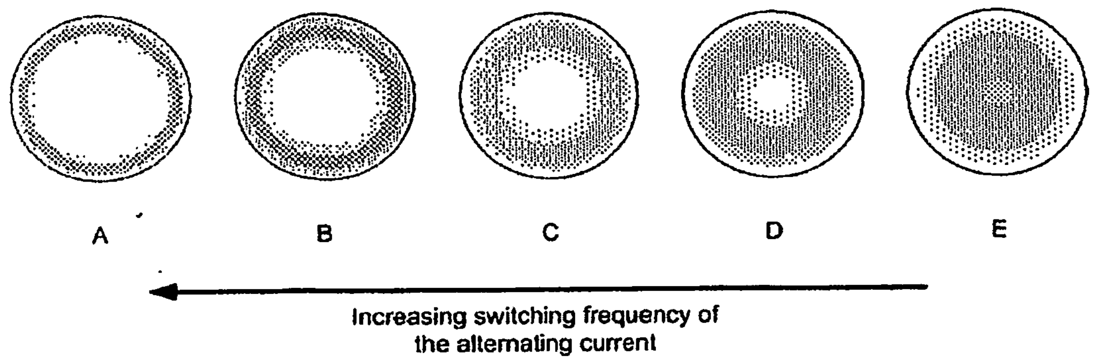
Drawing: Uniform current density in a conductor at saturation level.

Only at the saturation level is the electric current density (when applying DC) evenly distributed at the entire cross section of the conductor. The amount of electrical current to achieve this saturation level is extremely high and is mainly influenced by the cross section and conductivity (impedance) of the used conductor.



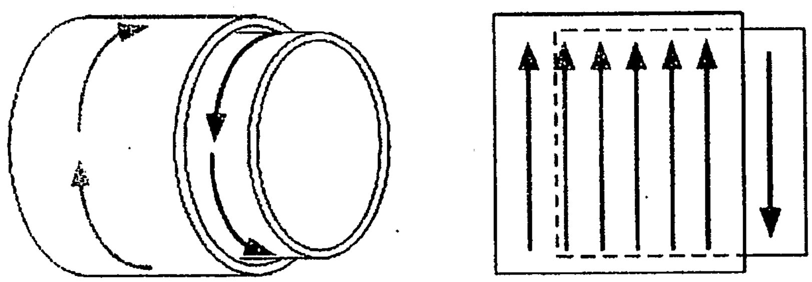
Drawing: Electric current traveling beneath or at the surface of the conductor (Skin-Effect).

It is also widely assumed that when passing through alternating current (like a radio frequency signal) through a conductor that the signal is passing through the skin layers of the conductor, called the Skin Effect. The chosen frequency of the alternating current defines the "Location / position" and "depth" of the Skin Effect. At high frequencies the electrical current will travel right at or near the surface of the conductor (A) while at lower frequencies (in the 5 to 10 Hz regions for a 20 mm diameter SH) the electrical alternating current will penetrate more the center of the shafts cross section (E). Also, the relative current density is higher in the current occupied regions at higher AC frequencies in comparison to the relative current density near the center of the shaft at very low AC frequencies (as there is more space available for the current to flow through).



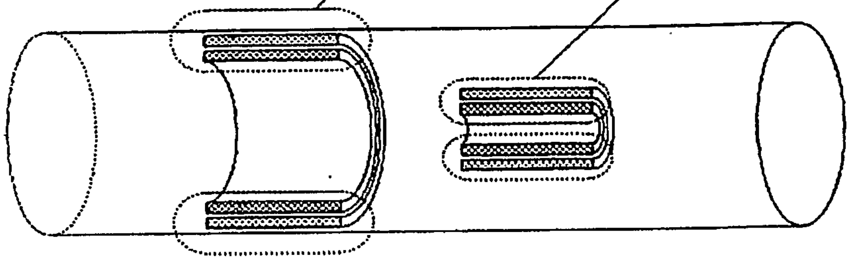
Drawing: The electrical current density of an electrical conductor (cross-section 90 deg to the current flow) when passing through the conductor an alternating current at different frequencies.

The desired magnetic field design of the PCME sensor technology are two circular magnetic field structures, stored in two layers on top of each other ("Picky-Back"), and running in opposite direction to each other (Counter-Circular).



Drawing: Desired magnetic sensor structure: two endless magnetic loops placed on top of each other, running in opposite directions to each other: Counter-Circular "Picky-Back" Field Design.

To make this magnetic field design highly sensitive to mechanical stresses that will be applied to the SH (shaft), and to generate the largest sensor signal possible, the desired magnetic field structure has to be placed nearest to the shaft surface. Placing the circular magnetic fields to close to the center of the SH will cause damping of the user available sensor-output-signal slope (most of the sensor signal will travel through the Ferro-magnetic shaft material as it has a much higher permeability in comparison to air), and increases the non-uniformity of the sensor signal (in relation to shaft rotation and to axial movements of the shaft in relation to the secondary sensor.



Drawing: Magnetic field structures stored near the shaft surface and stored near the center of the shaft.

It may be difficult to achieve the desired permanent magnetic encoding of the SH when using AC (alternating current) as the polarity of the created magnetic field is constantly changing and therefore may act more as a Degaussing system.

The PCME technology requires that a strong electrical current ("uni-polar" or DC, to prevent erasing of the desired magnetic field structure) is traveling right below the shaft surface (to ensure that the sensor signal will be uniform and measurable at the outside of the shaft). In addition a Counter-Circular, "picky back" magnetic field structure needs to be formed.

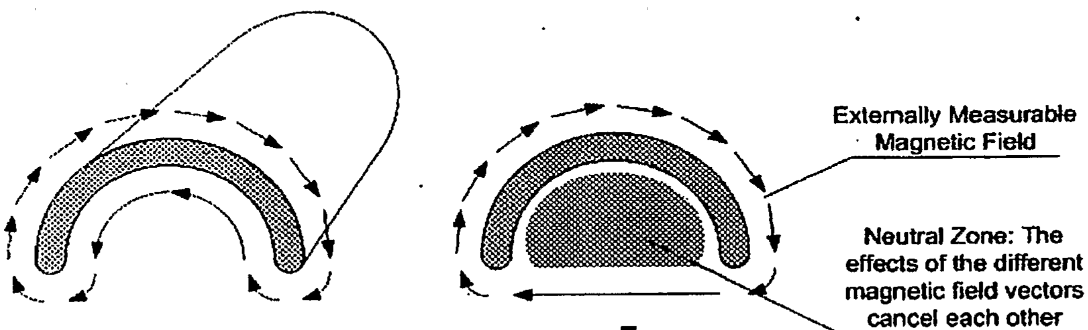
It is possible to place the two Counter-Circular magnetic field structures in the shaft by storing them into the shaft one after each other. First the inner layer will be stored in the SH, and then the outer layer by using a weaker magnetic force (preventing that the inner layer will be neutralized and deleted by accident. To achieve this, the known "permanent" magnet encoding techniques can be applied as described in patents from FAST technology, or by using a combination of electrical current encoding and the "permanent" magnet encoding.

A much simpler and faster encoding process uses "only" electric current to achieve the desired Counter-Circular "Picky-Back" magnetic field structure. The most challenging part here is to generate the Counter-Circular magnetic field.

A uniform electrical current will produce a uniform magnetic field, running around the electrical conductor in a 90 deg angle, in relation to the current direction (A). When placing two conductors side-by-side (B) then the magnetic field between the two conductors seems to cancel-out the effect of each other (C). Although still present, there is no detectable (or measurable) magnetic field between the closely placed two conductors. When placing a number of electrical conductors side-by-side (D) the "measurable" magnetic field seems to go around the outside the surface of the "flat" shaped conductor.

Drawing: The magnetic effects when looking at the cross-section of a conductor with a uniform current flowing through them.

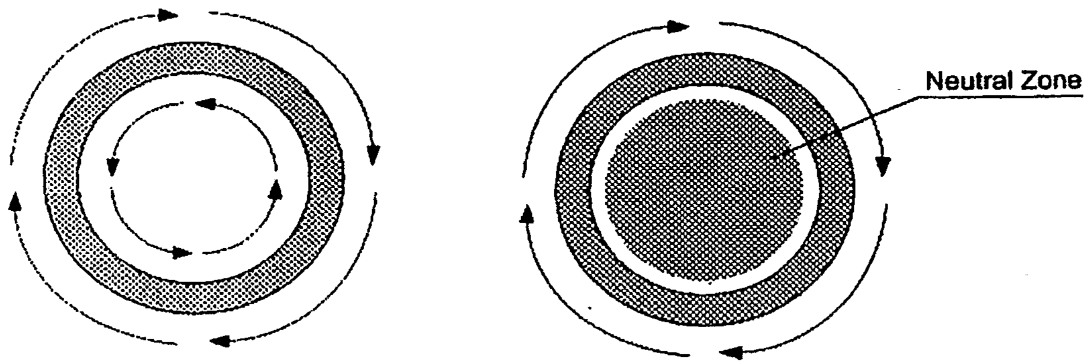
The "flat" or rectangle shaped conductor has now been bent into a "U"-shape. When passing an electrical current through the "U"-shaped conductor then the magnetic field following the outer dimensions of the "U"-shape is canceling out the measurable effects in the inner halve of the "U".



Drawing: The zone inside the "U"-shaped conductor seem to be magnetically "Neutral" when an electrical current is flowing through the conductor.

When no mechanical stress is applied to the cross-section of a "U"-shaped conductor it seems that there is no magnetic field present inside of the "U" (F). But when bending or twisting the "U"-shaped conductor the magnetic field will no longer follow its original path (90 deg angle to the current flow). Depending on the applied mechanical forces, the magnetic field begins to change slightly its path. At that time the magnetic-field-vector that is caused by the mechanical stress can be sensed and measured at the surface of the conductor, inside and outside of the "U"-shape. Note: This phenomena is applies only at very specific electrical current levels.

The same applies to the "O"-shaped conductor design. When passing a uniform electrical current through an "O"-shaped conductor (Tube) the measurable magnetic effects inside of the "O" (Tube) have canceled-out each other (G).



G H

Drawing: The zone inside the "O"-shaped conductor seem to be magnetically "Neutral" when an electrical current is flowing through the conductor.

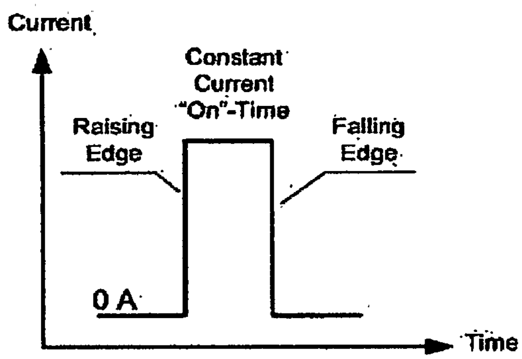
However, when mechanical stresses are applied to the "O"-shaped conductor (Tube) it becomes evident that there has been a magnetic field present at the inner side of the "O"-shaped conductor. The inner, counter directional magnetic field (as well as the outer magnetic field) begins to tilt in relation to the applied torque stresses. This tilting field can be clearly sensed and measured.

Encoding Pulse Design

To achieve the desired magnetic field structure (Counter-Circular, Picky-Back, Fields Design) inside the SH, according to an exemplary embodiment of a method of the present invention, unipolar electrical current pulses are passed through the Shaft (or SH). By using "pulses" the desired "Skin-Effect" can be achieved. By using a "unipolar" current direction (not changing the direction of the electrical current) the generated magnetic effect will not be erased accidentally.

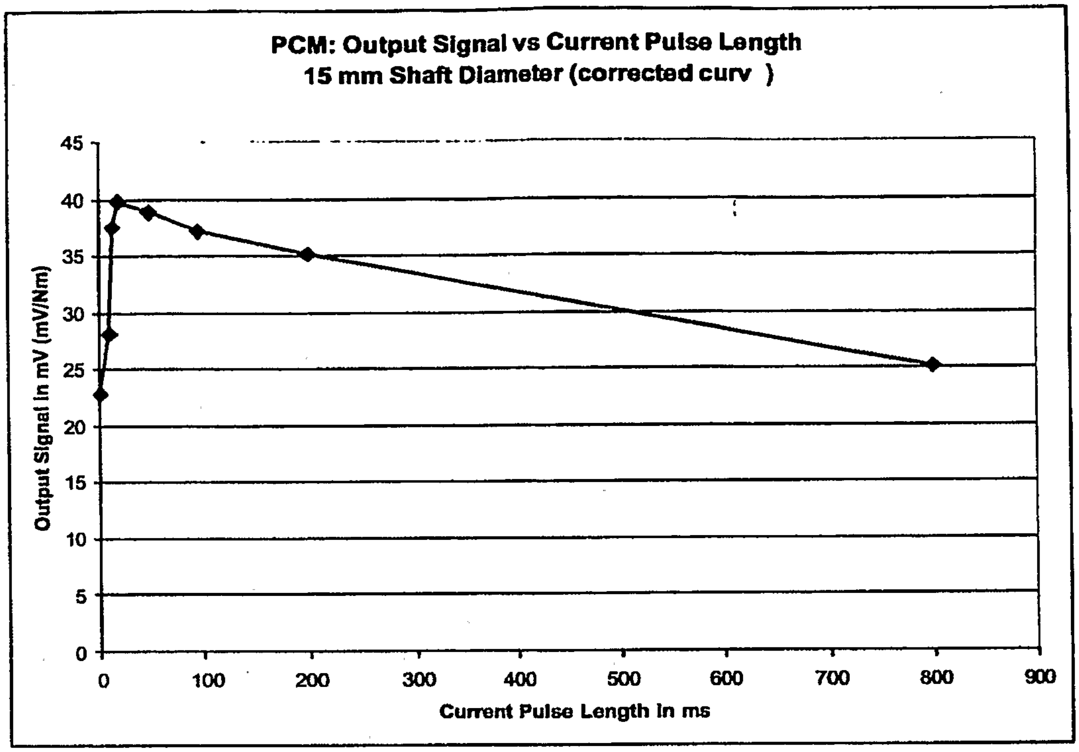
The used current pulse shape is most critical to achieve the desired PCME sensor design. Each parameter has to be accurately and repeatable controlled: Current raising time, Constant current on-time, Maximal current amplitude, and Current falling time. In addition it is very critical that the current enters and exits very uniformly around the entire shaft surface.

Rectangle Current Pulse Shape



Graph: Rectangle shaped electrical current pulse

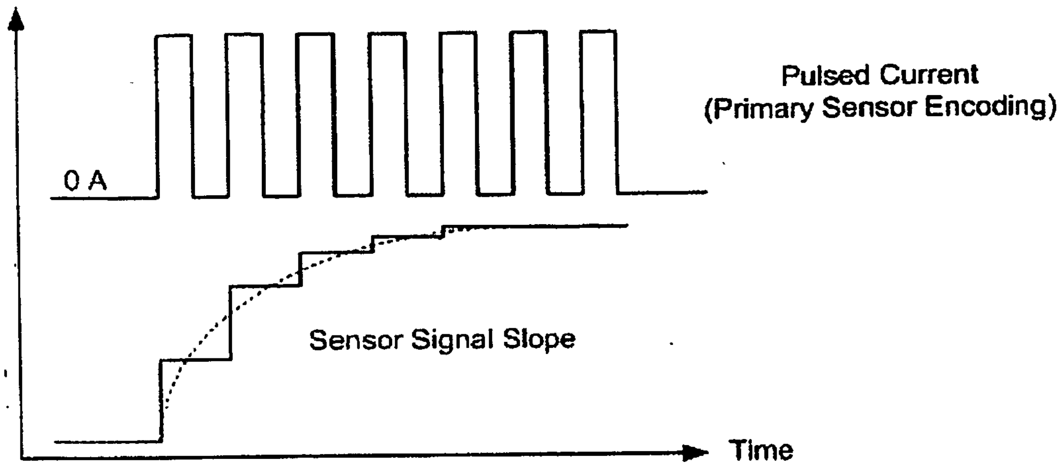
A rectangle shaped current pulse has a fast raising positive edge and a fast falling current edge. When passing a rectangle shaped current pulse through the SH, the raising edge is responsible for forming the targeted magnetic structure of the PCME sensor while the flat "on" time and the falling edge of the rectangle shaped current pulse are counter productive.



Graph: Relationship between rectangles shaped Current Encoding Pulse-Width (Constant Current On-Time) and Sensor Output Signal Slope.

In the following example a rectangle shaped current pulse has been used to generate and store the Couter-Circilar "Picky-Back" field in a 15 mm diameter, 14CrNi14 shaft. The pulsed electric current had its maximum at around 270 Ampere. The pulse "on-time" has been electronically controlled. Because of the high frequency component in the rising and falling edge of the encoding pulse, this experiment can not truly represent the effects of a true DC encoding SH. Therefore the Sensor-Output-Signal Slope-curve eventually flattens-out at above 20 mV/Nm when passing the Constant-Current On-Time of 1000 ms.

Without using a fast raising current-pulse edge (like using a controlled ramping slope) the sensor output signal slope would have been very poor (below 10 mV/Nm). Note: In this experiment (using 14CrNi14) the signal hysteresis was around 0.95% of the FS signal (FS = 75 Nm torque).

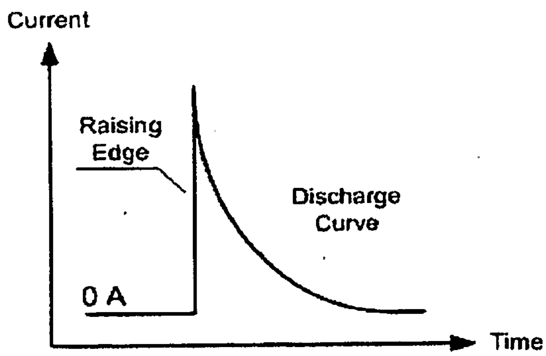


Graph: Increasing the Sensor-Output Signal-Slope by using several rectangle shaped current pulses in succession.

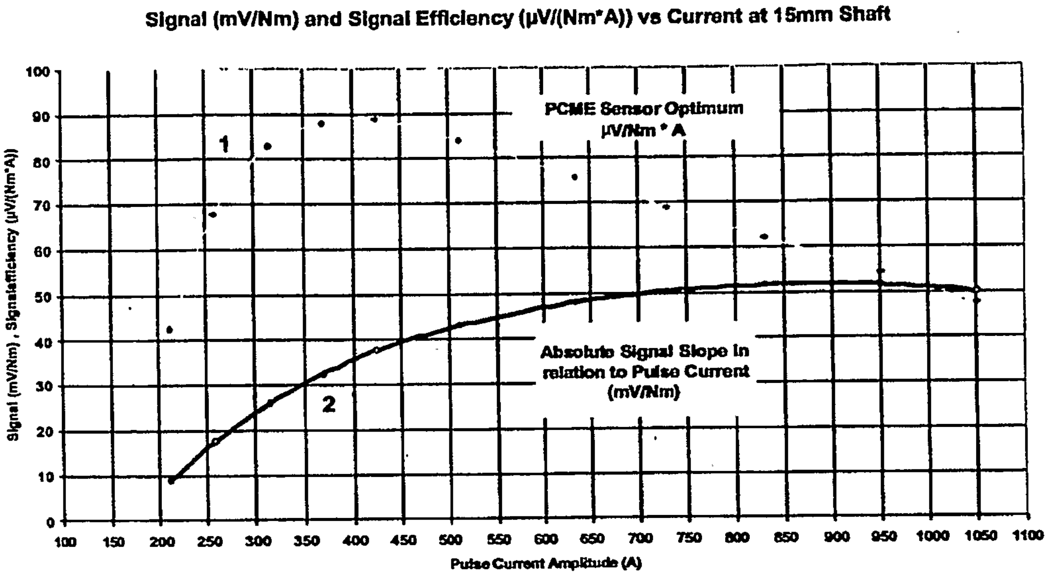
The Sensor-Output-Signal slope can be improved when using several rectangle shaped current-encoding-pulses in successions. In comparisons to other encoding-pulse-shapes the fast falling current-pulse signal slope of the rectangle shaped current pulse will prevent that the Sensor-Output-Signal slope may ever reach an optimal performance level. Meaning that after only a few current pulses (2 to 10) have been applied to the SH (or Shaft) the Sensor-Output Signal-Slope will no longer rise.

Discharge Current Pulse Shape

The Discharge-Current-Pulse has no Constant-Current ON-Time and has no fast falling edge. Therefore the primary and most felt effect in the magnetic encoding of the SH is the fast raising edge of this current pulse type.

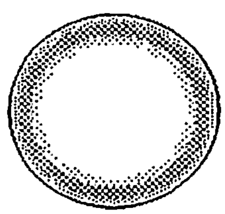


Graph: Sharp raising current edge and a typical discharging curve provides best results when creating a PCME sensor.



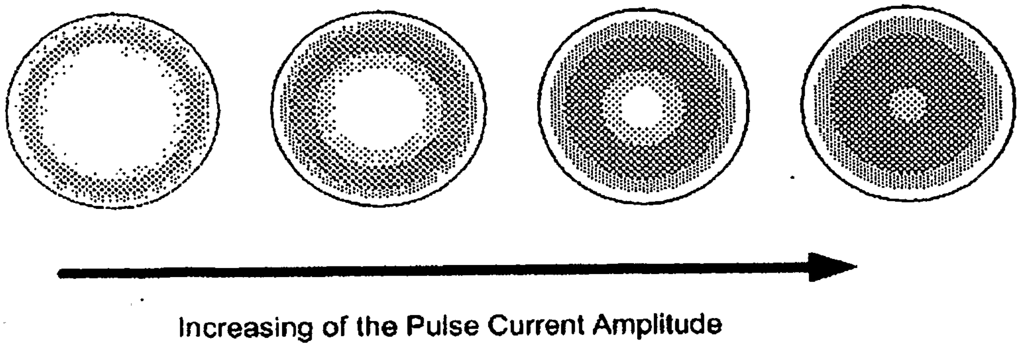
Graph: PCME Sensor-Output Signal-Slope optimization by identifying the right pulse current.

At the very low end of the pulse current scale (0 to 75 A for a 15 mm diameter shaft, 14CrNi14 shaft material) the "Discharge-Current-Pulse type is not powerful enough to cross the magnetic threshold needed to create a lasting magnetic field inside the Ferro magnetic shaft. When increasing the pulse current amplitude the double circular magnetic field structure begins to form below the shaft surface. As the pulse current amplitude increases so does the achievable torque sensor-output signal-amplitude of the secondary sensor system. At around 400A to 425A the optimal PCME sensor design has been achieved (the two counter flowing magnetic regions have reached their most optimal distance to each other and the correct flux density for best sensor performances.



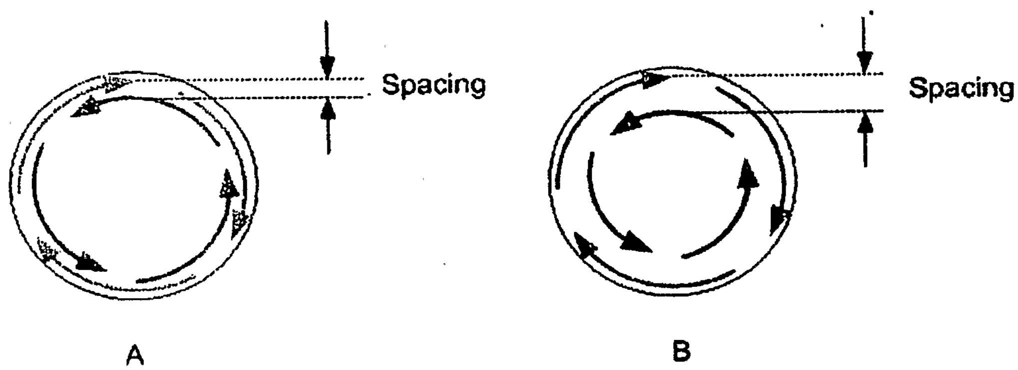
Drawing: Sensor Host (SH) cross section with the optimal PCME electrical current density and location during the encoding pulse.

When increasing further the pulse current amplitude the absolute, torque force related, sensor signal amplitude will further increase (curve 2) for some time while the overall PCME-typical sensor performances will decrease (curve 1). When passing 900A Pulse Current Amplitude (for a 15 mm diameter shaft) the absolute, torque force related, sensor signal amplitude will begin to drop as well (curve 2) while the PCME sensor performances are now very poor (curve 1).



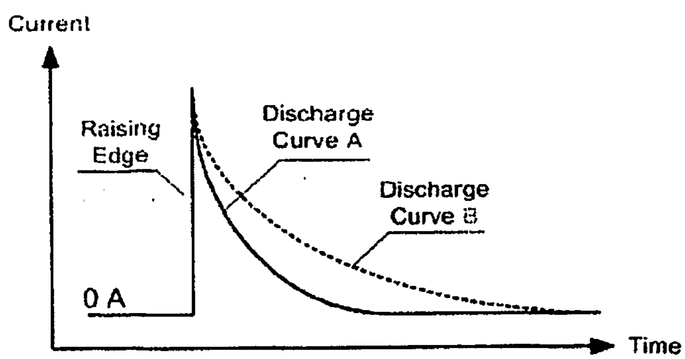
Drawing: Sensor Host (SH) cross sections and the electrical pulse current density at different and increasing pulse current levels.

As the electrical current occupies a larger cross section in the SH the spacing between the inner circular region and the outer (near the shaft surface) circular region becomes larger.



Drawing: Better PCME sensor performances will be achieved when the spacing between the Counter-Circular "Picky-Back" Field design is narrow (A).

The desired double, counter flow, circular magnetic field structure will be less able to create a close loop structure under torque forces which results in a decreasing secondary sensor signal amplitude.

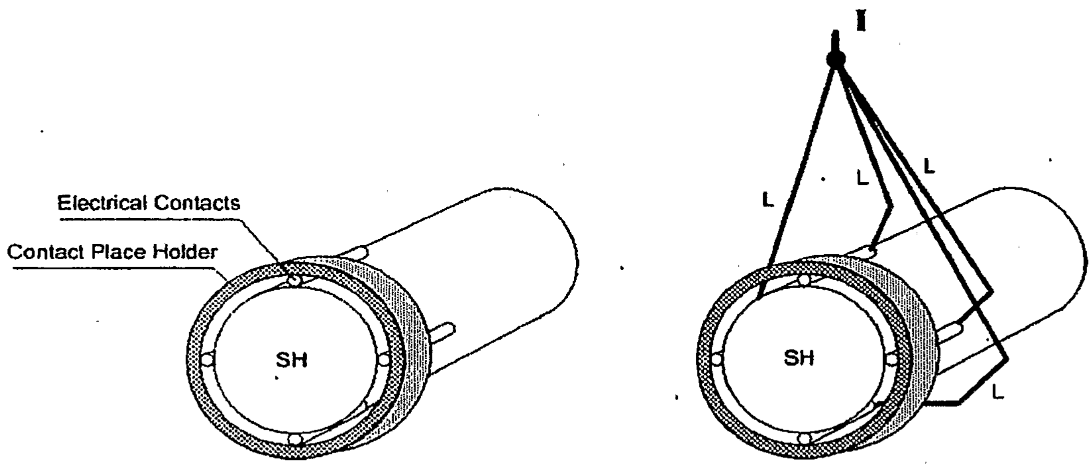


Graph: Flattening-out the current-discharge curve will also increase the Sensor-Output Signal-Slope.

When increasing the Current-Pulse discharge time (making the current pulse wider) (B) the Sensor-Output Signal-Slope will increase. However the required amount of current is very high to reduce the slope of the falling edge of the current pulse. It might be more practical to use a combination of a high current amplitude (with the optimal value) and the slowest possible discharge time to achieve the highest possible Sensor-Output Signal Slope.

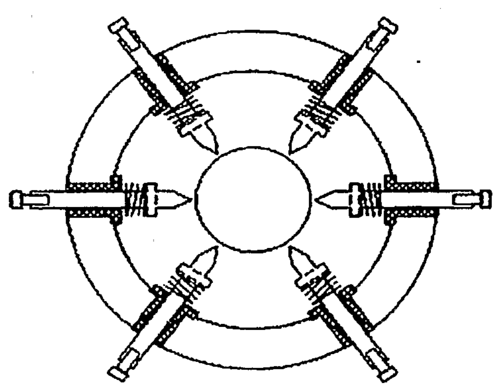
Primary Sensor Processing: Electrical Connection Devices

The PCME technology (it has to be noted that the term 'PCME' technology is used to refer to exemplary embodiments of the present invention) relies on passing through the shaft very high amounts of pulse-modulated electrical current at the location where the Primary Sensor should be produced. When the surface of the shaft is very clean and highly conductive a multi-point Cupper or Gold connection may be sufficient to achieve the desired sensor signal uniformity. Important is that the Impedance is identical of each connection point to the shaft surface. This can be best achieved when assuring the cable length (L) is identical before it joins the main current connection point (I)



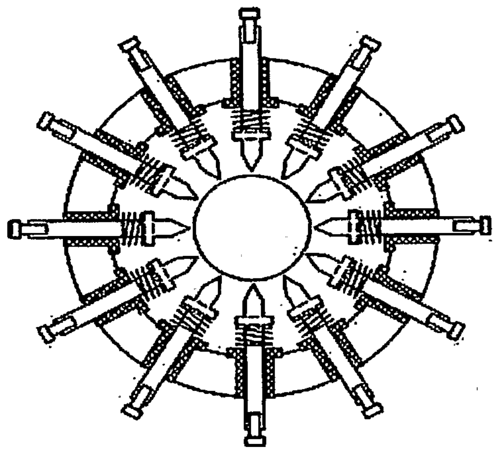
Drawing: Simple electrical multi-point connection to the shaft surface.

However, in most cases a reliable and repeatable multi-point electrical connection can be only achieved by ensuring that the impedance at each connection point is identical and constant. Using a spring pushed, sharpened connector will penetrate possible oxidation or isolation layers (maybe caused by finger prints) at the shaft surface.

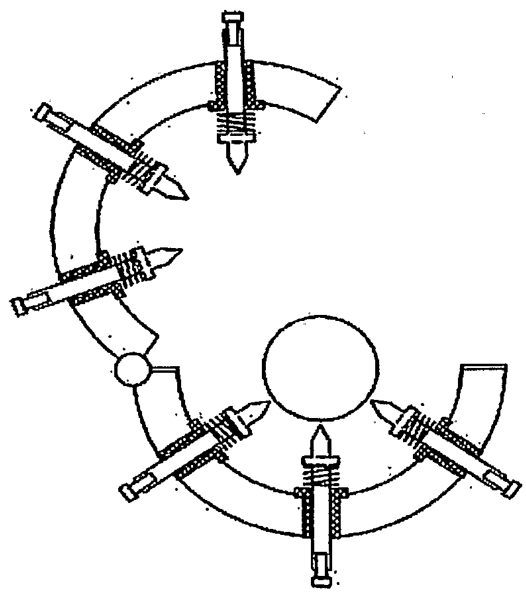


Drawing: Multi channel, electrical connecting fixture, with spring loaded contact points.

When processing the shaft it is most important that the electrical current is injected and extracted from the shaft in the most uniform way possible. The above drawing shows several electrical, from each other insulated, connectors that are held by a fixture around the shaft. This device is called a Shaft-Processing-Holding-Clamp (or SPHC). The number of electrical connectors required in a SPHC depends on the shafts outer diameter. The larger the outer diameter, the more connectors are required. The spacing between the electrical conductors has to be identical from one connecting point to the next connecting point. This method is called Symmetrical-"Spot"-Contacts.



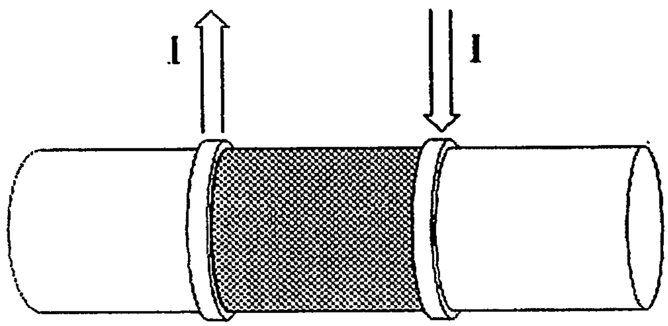
Drawing: Increasing the number of electrical connection points will assist the efforts of entering and exiting the Pulse-Modulated electrical current. It will also increase the complexity of the required electronic control system.



Drawing: Example of how to open the SPHC for easy shaft loading.

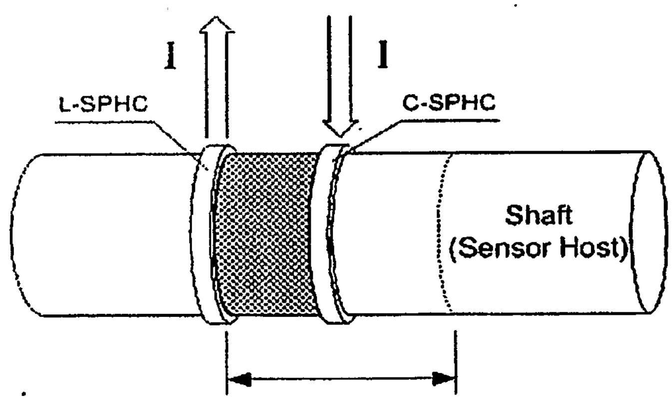
Primary Sensor Processing: Encoding

The encoding of the primary shaft can be done by using permanent magnets applied at a rotating shaft or using electric currents passing through the desired section of the shaft. When using permanent magnets a very complex, sequential procedure is necessary to put the two layers of closed loop magnetic fields, on top of each other, in the shaft. When using the PCME procedure the electric current has to enter the shaft and exit the shaft in the most symmetrical way possible to achieve the desired performances.



Drawing: Using two SPHCs (Shaft Processing Holding Clamps) that are placed at the borders of the planned sensing encoding region. Through one SPHC the pulsed electrical current (I) will enter the shaft, while at the second SPHC the pulsed electrical current (I) will exit the shaft. The region between the two SPHCs will then turn into the primary sensor.

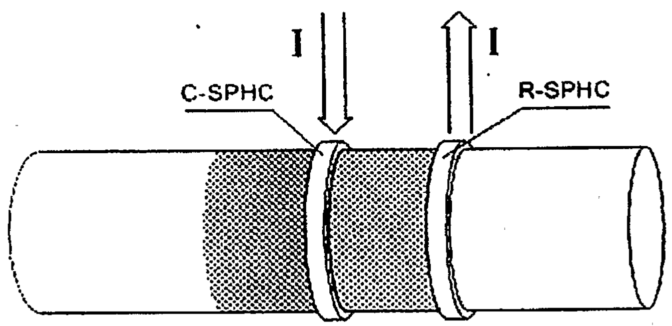
This particular sensor process will produce a Single Field (SF) encoded region. One benefit of this design (in comparison to those that are described below) is that this design is insensitive to any axial shaft movements in relation to the location of the secondary sensor devices. The disadvantage of this design is that when using axial (or in-line) placed MFS coils the system will be sensitive to magnetic stray fields (like the earth magnetic field).



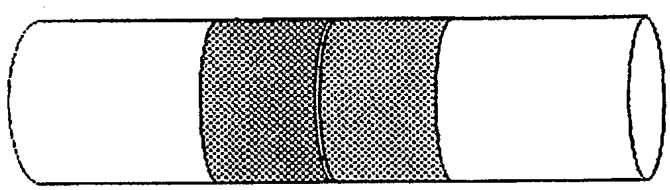
Drawing: A Dual Field (DF) encoded region (meaning two independent functioning sensor regions with opposite polarity, side-by-side) allows canceling the effects of uniform magnetic stray fields when using axial (or in-line) placed MFS coils. However, this

primary sensor design also shortens the tolerable range of shaft movement in axial direction (in relation to the location of the MFS coils). There are two ways to produce a Dual Field (DF) encoded region with the PCME technology. The sequential process, where the magnetic encoded sections are produced one after each other, and the parallel process, where both magnetic encoded sections are produced at the same time.

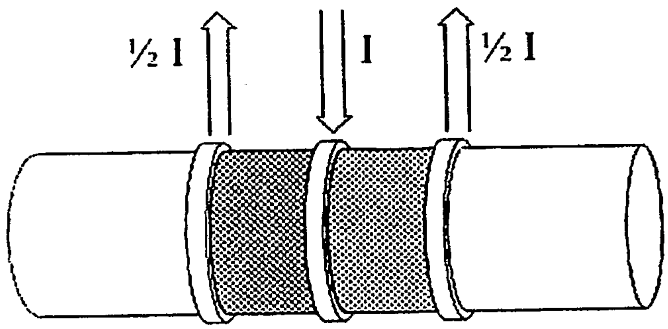
The first process step of the sequential dual field design is to magnetically encode one sensor section (identically to the Single Field procedure), whereby the spacing between the two SPHC has to be halve of the desired final length of the Primary Sensor region. To simplify the explanations of this process we call the SPHC that is placed in the center of the final Primary Sensor Region the Center SPHC (C-SPHC), and the SPHC that is located at the left side of the Center SPHC: L-SPHC.



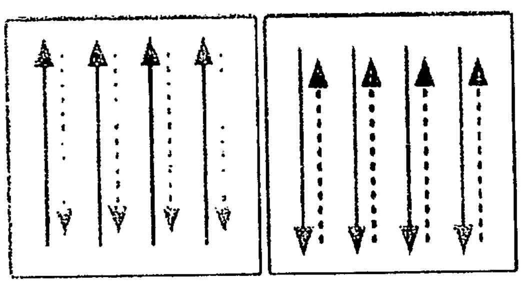
Drawing: The second process step of the sequential Dual Field encoding will use the SPHC that is located in the center of the Primary Sensor region (called C-SPHC) and a second SPHC that is placed at the other side (the right side) of the center SPHC, called R-SPHC. Important is that the current flow direction in the center SPHC (C-SPHC) is identical at both process steps.



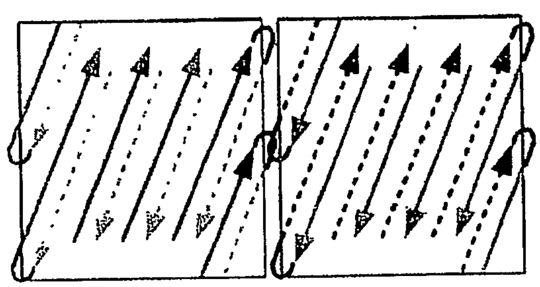
Drawing: The performance of the final Primary Sensor Region depends on how close the two encoded regions can be placed in relation to each other. And this is dependent on the design of the used center SPHC. The narrower the in-line space contact dimensions are of the C-SPHC, the better are the performances of the Dual Field PCME sensor.



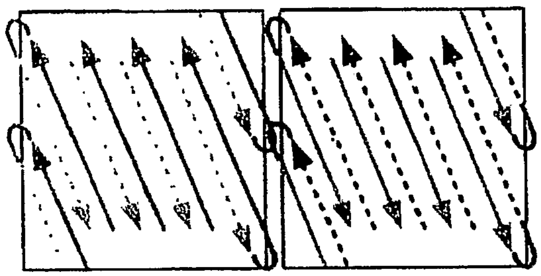
The above drawing shows the pulse application according to another exemplary embodiment of the present invention. As my be taken from the above drawing, the pulse is applied to three locations of the shaft. Due to the current distribution to both sides of the middle electrode where the current I is entered into the shaft, the current leaving the shaft at the lateral electrodes is only half the current entered at the middle electrode, namely ½ I. The electrodes are depicted as rings which dimensions are adapted to the dimensions of the outer surface of the shaft. However, it has to be noted that other electrodes may be used, such as the electrodes comprising a plurality of pin electrodes described later in this text.



Drawing: Magnetic flux directions of the two sensor sections of a Dual Field PCME sensor design when no torque is applied to the shaft. The counter flow magnetic flux loops do not interact with each other.



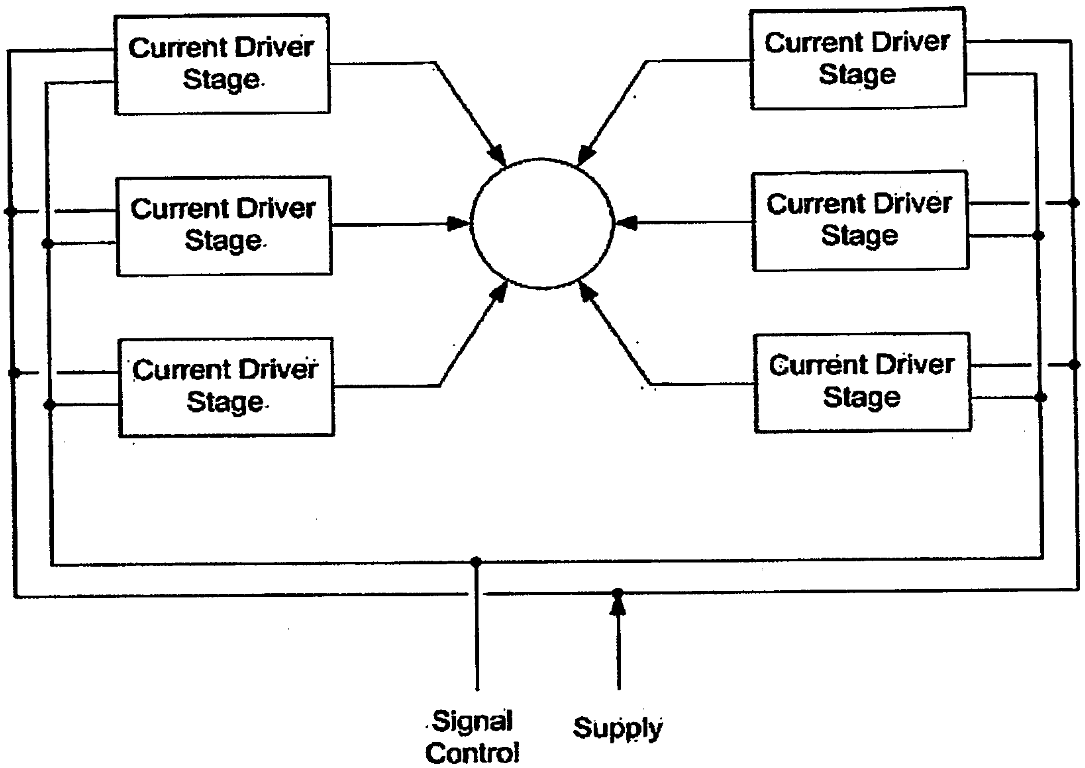
Drawing: When torque forces are applied in a particular direction then the magnetic flux loops begin to run with an increasing tilting angle inside the shaft. When the tilted magnetic flux reaches the PCME segment boundary then the flux line interacts with the counterflowing magnetic flux lines as shown above.



Drawing: When the applied torque direction is changing (for example from clock-wise to counter-clock-wise) so will change the tilting angle of the counterflow magnetic flux structures inside the PCM Encoded shaft.

Multi Channel Current Driver for Shaft Processing

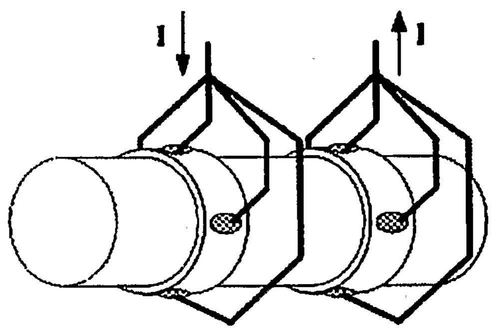
In cases where an absolute identical impedance of the current path to the shaft surface can not be guaranteed, then electric current controlled driver stages can be used to overcome this problem.



Drawing: A six-channel synchronized Pulse current driver system for small diameter Sensor Hosts (SH). As the shaft diameter increases so will the number of current driver channels.

From Bras Ring Contacts to Symmetrical "Spot" Contacts

When the shaft diameter is relative small and the shaft surface is clean and free from any oxidations at the desired Sensing Region, then a simple "Bras"-ring (or Copper-ring) contact method can be chosen to process the Primary Sensor.

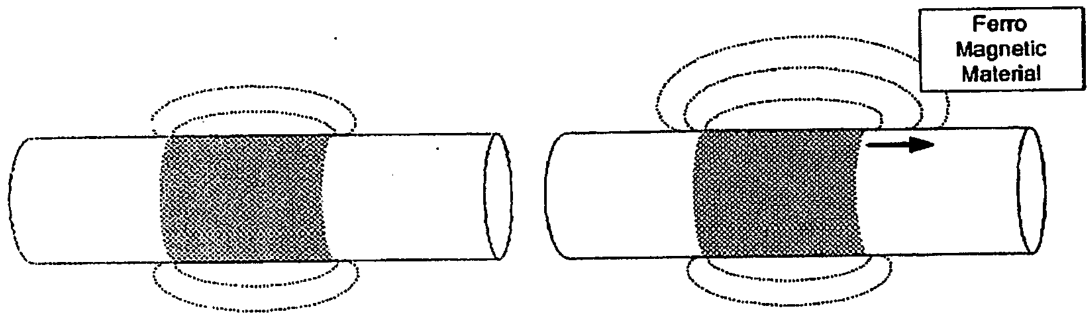


Drawing: Bras-rings (or Copper-rings) tightly fitted to the shaft surface, with solder connections for the electrical wires. The area between the two Bras-rings (Copper-rings) is the encoded region.

However, it is very likely that the achievable RSU performances are much lower then when using the Symmetrical "Spot" Contact method.

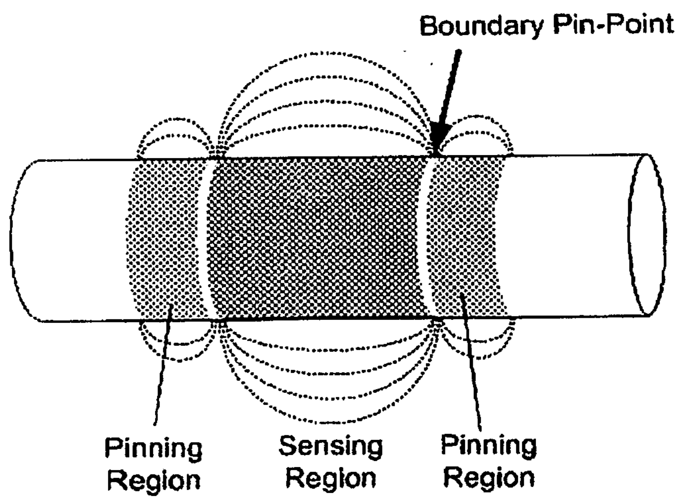
Hot-Spotting

A standard single field (SF) PCME sensor has very poor Hot-Spotting performances. The external magnetic flux profile of the SF PCME sensor segment (when torque is applied) is very sensitive to possible changes (in relation to Ferro magnetic material) in the nearby environment. As the magnetic boundaries of the SF encoded sensor segment are not well defined (not "Pinned Down") they can "extend" towards the direction where Ferro magnet material is placed near the PCME sensing region.



Drawing: A PCME process magnetized sensing region is very sensitive to Ferro magnetic materials that may come close to the boundaries of the sensing regions.

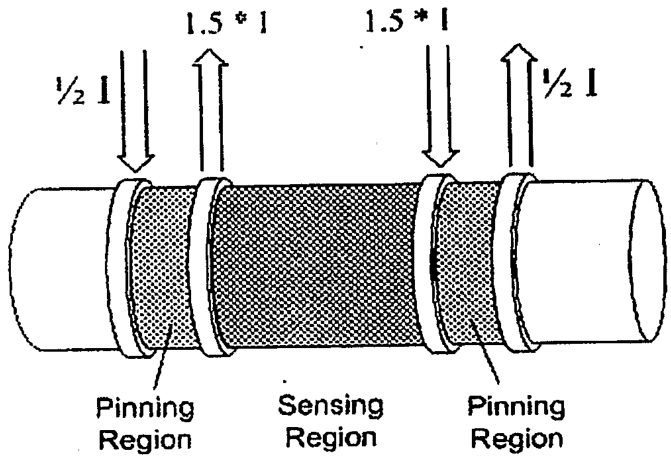
To reduce the Hot-Spotting sensor sensitivity the PCME sensor segment boundaries have to be better defined by pinning them down (they can no longer move).



Drawing: PCME processed Sensing region with two "Pinning Field Regions", one on each side of the Sensing Region.

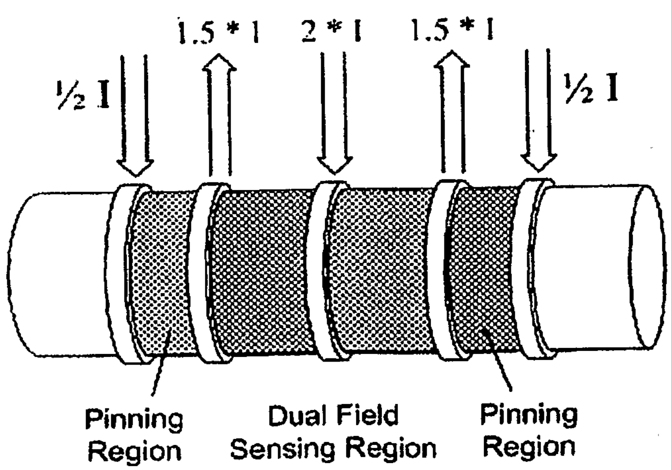
By placing Pinning Regions closely on either side the Sensing Region, the Sensing Region Boundary has been pinned down to a very specific location. When Ferro magnetic material is coming close to the Sensing Region, it may have an effect on the outer boundaries of the Pinning Regions, but it will have very limited effects on the Sensing Region Boundaries.

There are a number of different ways, according to exemplary embodiments of the present invention how the SH (Sensor Host) can be processed to get a Single Field (SF) Sensing Region and two Pinning Regions, one on each side of the Sensing Region. Either each region is processed after each other (Sequential Processing) or two or three regions are processed simultaneously (Parallel Processing). The Parallel Processing provides a more uniform sensor (reduced parasitic fields) but requires much higher levels of electrical current to get to the targeted sensor signal slope.



Drawing: Parallel Processing example for a Single Field (SF) PCME sensor with Pinning Regions on either side of the main sensing region, in order to reduce (or even eliminate) Hot-Spotting.

A Dual Field PCME Sensor is less sensitive to the effects of Hot-Spotting as the sensor center region is already Pinned-Down. However, the remaining Hot-Spotting sensitivity can be further reduced by placing Pinning Regions on either side of the Dual-Field Sensor Region.

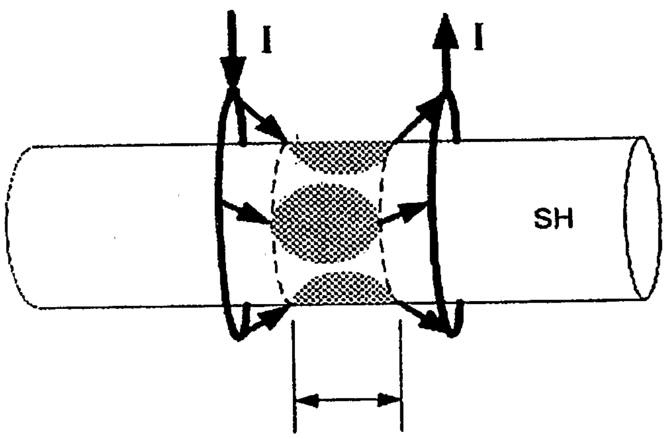


Drawing: Dual Field (DF) PCME sensor with Pinning Regions either side.

When Pinning Regions are not allowed or possible (example: limited axial spacing available) then the Sensing Region has to be magnetically shielded from the influences of external Ferro Magnetic Materials.

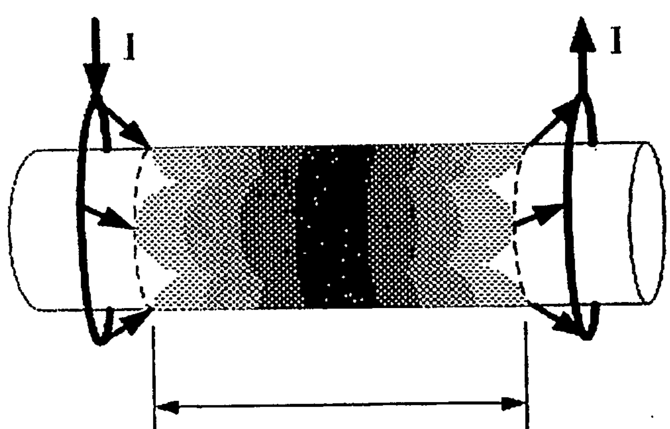
RSU

The RSU sensor performance are, according to current understanding, mainly depending on how circumferentially uniform the electrical current entered and exited the SH surface, and the physical space between the electrical current entry and exit points. The larger the spacing between the current entry and exit points, the better is the RSU performance.



PCM Encoding Segment

Drawing: When the spacings between the individual circumferential placed current entry points are relatively large in relation to the shaft diameter (and equally large are the spacings between the circumferentially placed current exit points) then this will result in very poor RSU performances. In such a case the length of the PCM Encoding Segment has to be as large as possible as otherwise the created magnetic field will be circumferentially non-uniform.



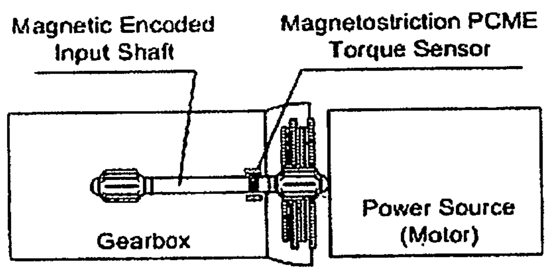
PCM Encoding Segment

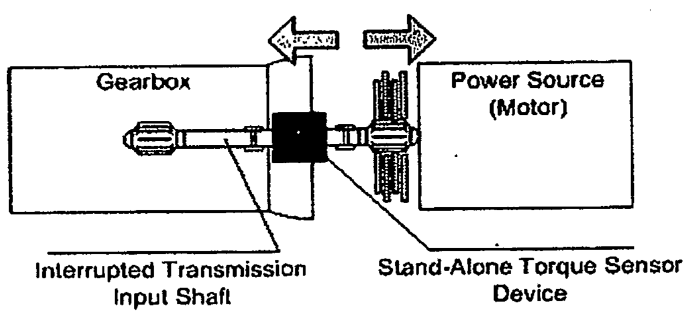
Drawing: By widening the PCM Encoding Segment the circumferentially magnetic field distribution will become more uniform (and eventually almost perfect) at the halve distance between the current entry and current exit points. Therefore the RSU performance of the PCME sensor is best at the halve way-point between of the current-entry / current-exit points.

Description of the basic design issues of a NCT sensor system

Without going into the specific details of the PCM-Encoding technology, the end-user of this sensing technology need to now some design details that will allow him to apply and to use this sensing concept in his application. The following pages describe the basic elements of a magnetostriction based NCT sensor (like the primary sensor, secondary sensor, and the SCSP electronics), what the individual components look like, and what choices need to be made when integrating this technology into an already existing product.

In principle the PCME sensing technology can be used to produce a stand-alone sensor product. However, in already existing industrial applications there is little to none space available for a "stand-alone" product. The PCME technology can be applied in an existing product without the need of redesigning the final product.

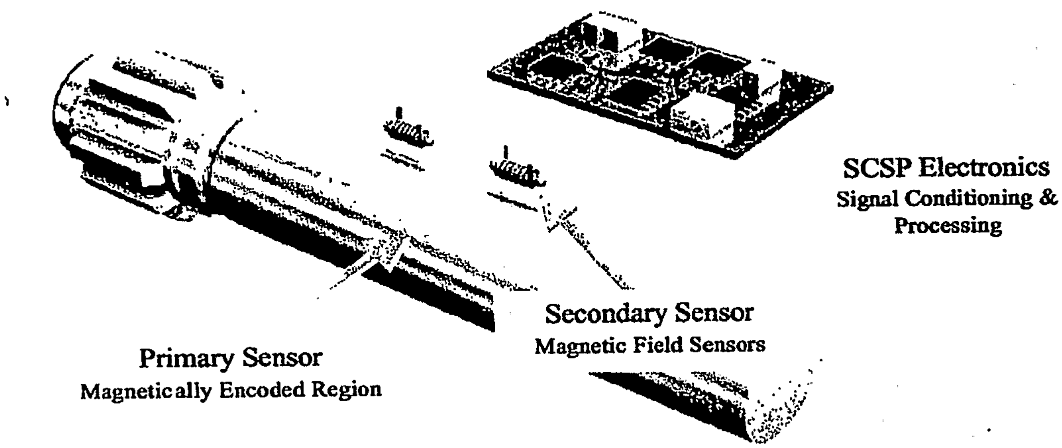




In case a stand-alone torque sensor device will be applied to a motor – transmission system it may require that the entire system need to undergo a major design change.

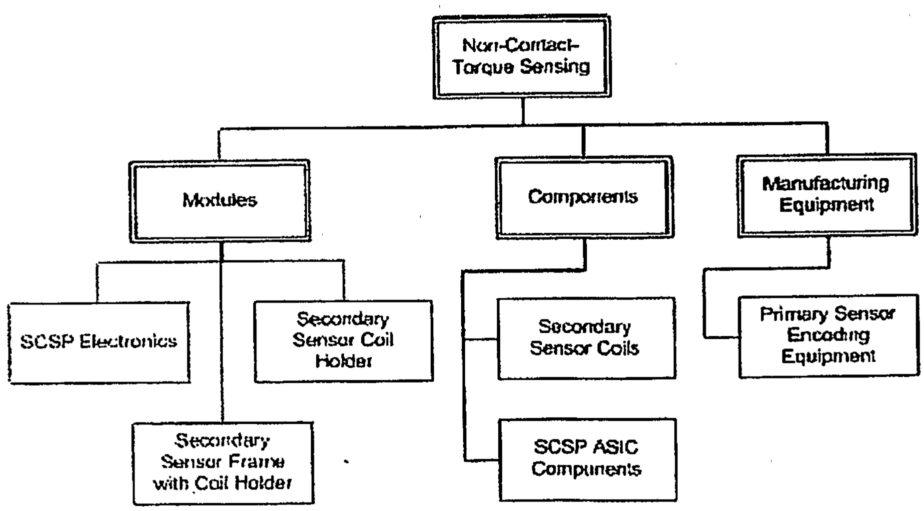
Sensor Components

The non-contact magnetostriction torque-sensor (NCT-Sensor) consists, according to an exemplary embodiment of the present invention, of three main functional elements: The ***Primary Sensor***, the ***Secondary Sensor***, and the ***Signal Conditioning & Signal Processing*** (SCSP) electronics.



Depending on the application type (volume and quality demands, targeted manufacturing cost, manufacturing process flow) the customer can chose to purchase either the ***individual components*** to build the sensor system under his own management, or can subcontract the production of the ***individual modules***.

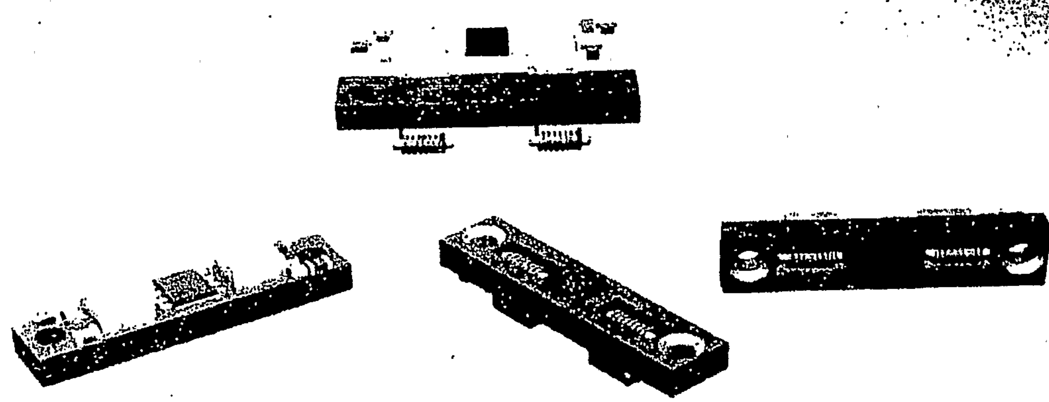
In cases where the annual production target is in the thousands of units it may be more efficient to integrate the "primary-sensor magnetic-encoding-process" into the customers manufacturing process. In such a case the customer needs to purchase application specific "magnetic encoding equipment".



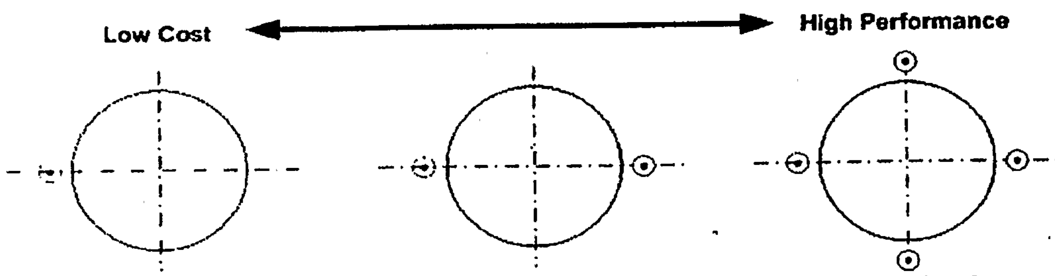
In high volume applications, where cost and the integrity of the manufacturing process are critical, it is typical that NCTE supplies only the individual basic components and equipment necessary to build a non-contact-torque sensor:

- ☐ ICs (surface mount packaged, Application-Specific Electronic Circuits)
- ☐ MFS-Coils (as part of the Secondary Sensor)
- ☐ Sensor Host Encoding Equipment (to apply the magnetic encoding on the shaft = Primary Sensor)

Depending on the required volume, the MFS-Coils can be supplied already assembled on a frame, and if desired, electrically attached to a wire harness with connector. Equally the SCSP (Signal Conditioning & Signal Processing) electronics can be supplied fully functional in PCB format, with or without the MFS-Coils embedded in the PCB.



The number of required MFS-coils is dependent on the expected sensor performance and the mechanical tolerances of the physical sensor design. In a well designed sensor system with perfect Sensor Host (SH or magnetically encoded shaft) and minimal interferences from unwanted magnetic stray fields, only 2 MFS-coils are needed. However, if the SH is moving radial or axial in relation to the secondary sensor position by more than a few tenths of a millimeter, then the number of MFS-coils need to be increased to achieve the desired sensor performance.



Cross Section of Primary Sensor (Shaft) and one pair of MFS-coils

Two pairs of MFS-coils

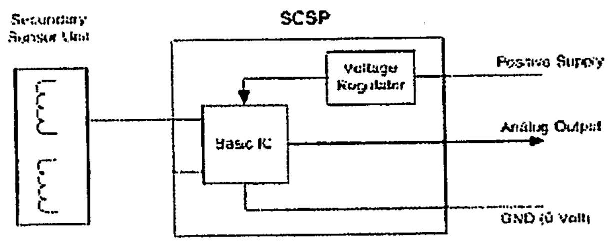
Four pairs of MFS-coils

Control and/or evaluation circuitry

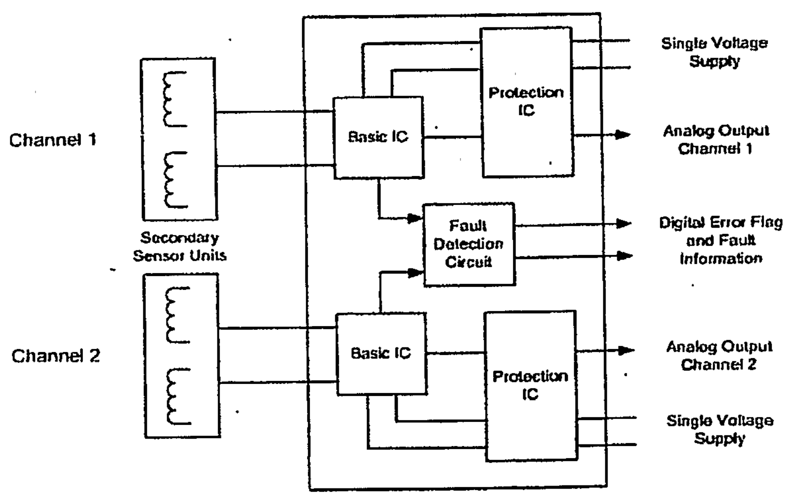
The SCSP electronics, according to an exemplary embodiment of the present invention, consist of the NCTE specific ICs, a number of external passive and active electronic circuits, the printed circuit board (PCB), and the SCSP housing or casing. Depending on the environment where the SCSP unit will be used the casing has to be sealed appropriately.

Depending on the application specific requirements NCTE (according to an exemplary embodiment of the present inevention) offers a number of different application specific circuits:

- ☐ Basic Circuit
- ☐ Basic Circuit with integrated Voltage Regulator
- ☐ High Signal Bandwidth Circuit
- ☐ Optional High Voltage and Short Circuit Protection Device
- ☐ Optional Fault Detection Circuit



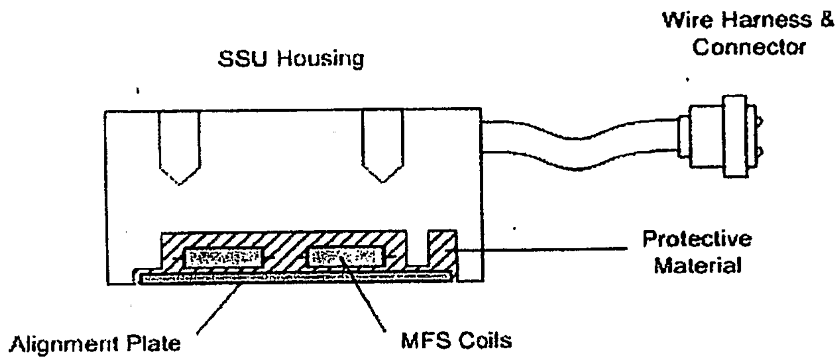
Example 1: Single channel, low cost sensor electronics solution



Example 2: Dual channel, short circuit protected system design with integrated fault detection. This design consists of 5 ASIC devices and provides a high degree of system safety. The Fault-Detection IC identifies when there is a wire breakage anywhere in the sensor system, a fault with the MFS coils, or a fault in the electronic driver stages of the "Basic IC".

Secondary Sensor Unit

The Secondary Sensor consists of the elements: One to eight **MFS** (Magnetic Field Sensor) Coils, the **Alignment- & Connection-Plate**, the wire harness with connector, and the **Secondary-Sensor-Housing**.



The MFS-coils are mounted onto the alignment-Plate. Usually the Alignment-Plate allows that the two connection wires of each MFS-Coil are soldered / connected in the appropriate way. The wire harness is connected to the alignment plate. This, completely assembled with the MFS-Coils and wire harness, is then embedded or held by the Secondary-Sensor-Housing.

The main element of the MFS-Coil is the core wire, which has to be made out of an amorphous-like material.

Depending on the environment where the Secondary-Sensor-Unit will be used, the assembled Alignment Plate has to be covered by protective material. This material can not cause mechanical stress or pressure on the MFS-coils when the ambient temperature is changing.

In applications where the operating temperature will not exceed +110 deg C the customer has the option to place the SCSP electronics (ASIC) inside the secondary sensor unit (SSU). While the ASIC devices can operated at temperatures above +125 deg C it will become increasingly more difficult to compensate the temperature related signal-offset and signal-gain changes.

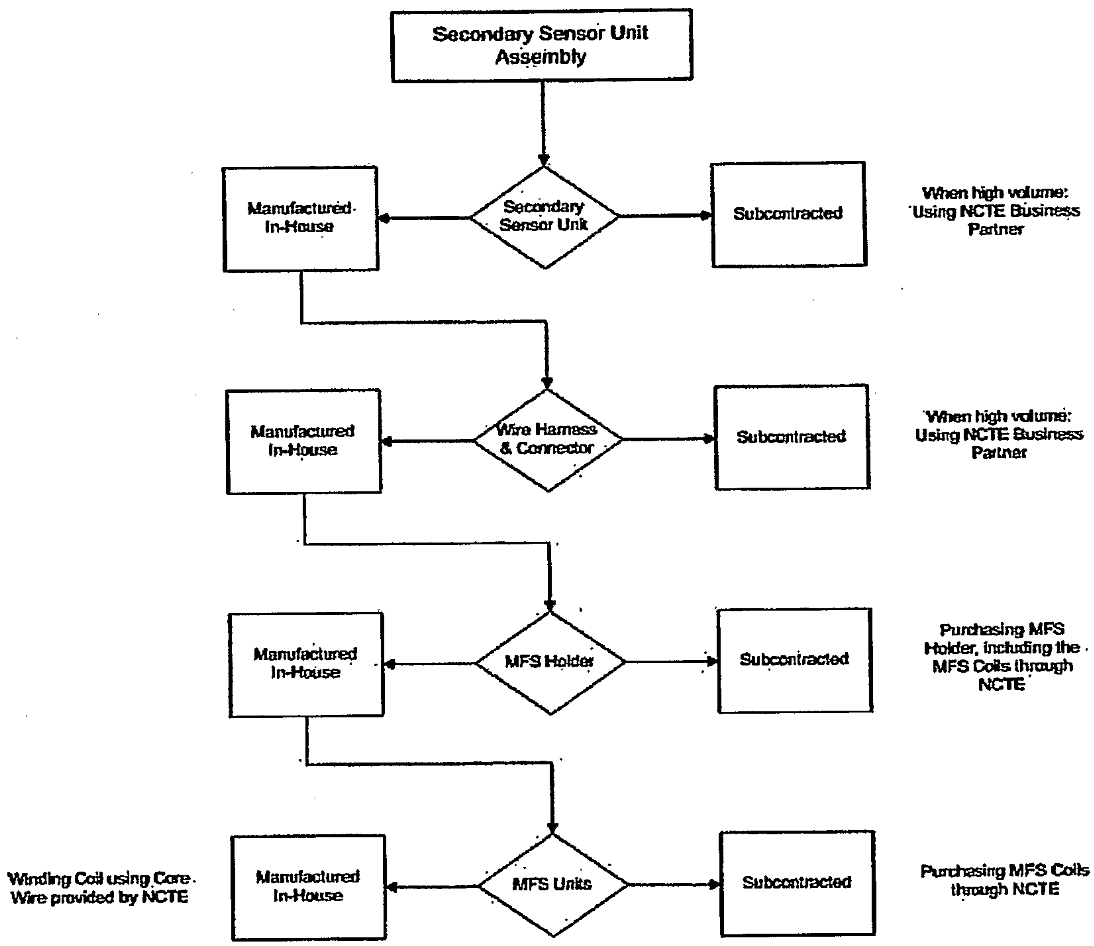
The recommended maximal cable length between the MFS-coils and the SCSP electronics is 2 meters. When using the appropriate connecting cable, distances of up to 10 meters are achievable. To avoid signal-cross-talk in multi-channel applications (two independent SSU's operating at the same Primary Sensor location = Redundant Sensor Function), specially shielded cable between the SSU's and the SCSP Electronics should be considered.

When planning to produce the Secondary-Sensor-Unit (SSU) the producer has to decide which part / parts of the SSU have to be purchased through subcontracting and which manufacturing steps will be made in-house.

Secondary Sensor Unit Manufacturing Options

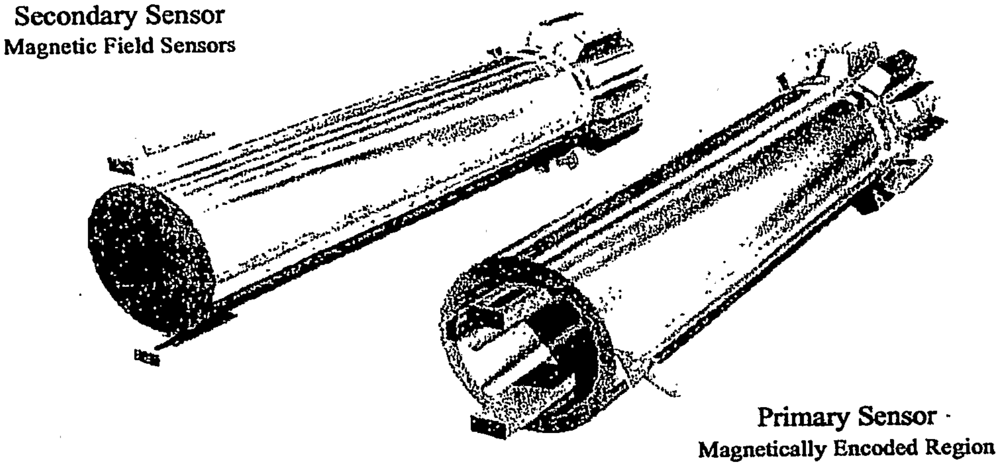
When integrating the NCT-Sensor into a customized tool or standard transmission system then the systems manufacturer has several options to choose from:

- ☐ custom made SSU (including the wire harness and connector)
- ☐ selected modules or components; the final SSU assembly and system test may be done under the customer's management.
- ☐ only the essential components (MFS-coils or MFS-core-wire, Application specific ICs) and will produce the SSU in-house.

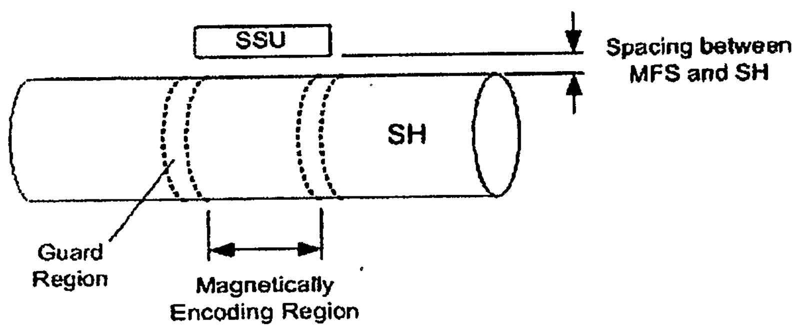


Primary Sensor Design

The SSU (Secondary Sensor Units) can be placed outside the magnetically encoded SH (Sensor Host) or, in case the SH is hollow, inside the SH. The achievable sensor signal amplitude is of equal strength but has a much better signal-to-noise performance when placed inside the hollow shaft.



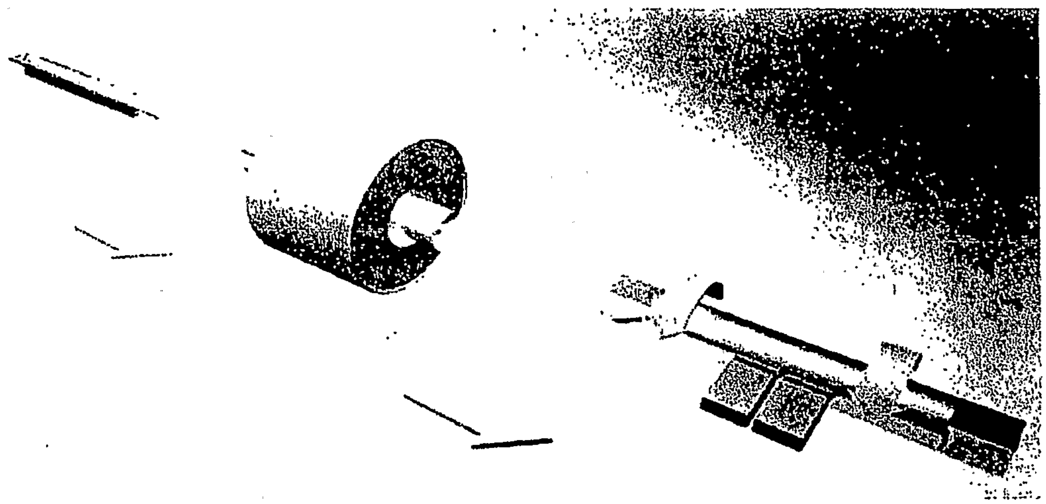
Improved sensor performances may be achieved when the magnetic encoding process is applied to a straight and parallel section of the SH (shaft). For a shaft with 15 mm to 25 mm diameter the optimal minimum length of the Magnetically Encoded Region is 25 mm. The sensor performances will further improve if the region can be made as long as 45 mm (adding Guard Regions). In complex and highly integrated transmission (gearbox) systems it will be difficult to find such space. Under more ideal circumstances the Magnetically Encoding Region can be as short as 14 mm, but this bears the risk that not all of the desired sensor performances can be achieved.



The spacing between the SSU (Secondary Sensor Unit) and the Sensor Host surface, according to an exemplary embodiment of the present invention, should be held as small as possible to achieve the best possible signal quality.

Primary Sensor Encoding Equipment

Depending on which magnetostriction sensing technology will be chosen, the Sensor Host (SH) needs to be processed and treated accordingly. The technologies vary by a great deal from each other (ABB, FAST, FT, Kubota, MDI, NCTE, RM, Siemens, ...) and so does the processing equipment required. Some of the available magnetostriction sensing technologies don't need any physical changes to be made on the SH and rely only on magnetic processing (MDI, FAST, NCTE).



While the MDI technology is a two phase process, the FAST technology is a three phase process, and the NCTE technology a one phase process, called PCM Encoding.

Note: Be aware that after the magnetic processing, the Sensor Host (SH or Shaft) has become a "precision measurement" device and has to be treated accordingly. The magnetic processing should be the very last step before the treated SH is carefully placed in its final location.

The magnetic processing should be an integral part of the customer's production process (in-house magnetic processing) under the following circumstances:

- ☐ High production quantities (like in the thousands)
- ☐ Heavy or difficult to handle SH (e.g. high shipping costs)
- ☐ Very specific quality and inspection demands (e.g. defense applications)

In all other cases it may be more cost effective to get the SH magnetically treated by a qualified and authorized subcontractor, such as NCTE. For the "in-house" magnetic processing dedicated manufacturing equipment is required. Such equipment can be operated fully manually, semi-automated, and fully automated. Depending on the complexity and automation level the equipment can cost anywhere from EUR 20k to above EUR 500k.

In this application, there are a number of "new" acronyms used as otherwise some explanations and descriptions may be difficult to read. While the acronyms "ASIC", "IC", and "PCB" are already market standard definitions, there are many new terms that have been created in relation to the magnetostriction based NCT sensing technology. It should be noted that in this application, when there is a reference to NCT technology, it is referred to exemplary embodiments of the present invention.

Acronym	**Description**	**Category**
ASIC	Application Specific IC	Electronics
DF	Dual Field	Primary Sensor
EMF	Earth Magnetic Field	Test Criteria
FS	Full Scale	Test Criteria
Hot-Spotting	Sensitivity to nearby Ferro magnetic material	Specification
IC	Integrated Circuit	Electronics
MFS	Magnetic Field Sensor	Sensor Component
NCT	Non Contact Torque	Technology
PCB	Printed Circuit Board	Electronics
PCME	Pulse Current Modulated Encoding	Technology
POC	Proof-of-Concept	
RSU	Rotational Signal Uniformity	Specification
SCSP	Signal Conditioning & Signal Processing	Electronics
SF	Single Field	Primary Sensor
SH	Sensor Host	Primary Sensor
SPHC	Shaft Processing Holding Clamp	Processing Tool
SSU	Secondary Sensor Unit	Sensor Component

According to an exemplary embodiment of the present invention, there is provided a torque sensor, comprising:

a first sensor element with a magnetically encoded region; and

a second sensor element with at least one magnetic field detector;

wherein the first sensor element has a surface;

wherein, in a direction essentially perpendicular to the surface of the first sensor element, the magnetically encoded region of the first sensor element has a magnetic field structure such that there is a first magnetic flow in a first direction and a second magnetic flow in a second direction;

wherein the first direction is opposite to the second direction;

wherein the first sensor element is a shaft;

wherein in a cross-sectional view of the shaft, there is a first circular magnetic flow having the first direction and a first radius and a second circular magnetic flow having the second direction and a second radius; and

wherein the first radius is larger than the second radius.

Abstract
The present invention relates to a torque sensor, comprising a first sensor element with a magnetically encoded region and a second sensor element with at least one magnetic field detector. The first sensor element has a surface. In a direction essentially perpendicular to the surface of the first sensor element, the magnetically encoded region of the first sensor element has a magnetic field structure such that there is a first magnetic flow in a first direction and a second magnetic flow in a second direction, wherein the first direction is opposite to the second direction.

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25.02.05

Bescheinigung | Certificate | Attestation

Die angehefteten Unterlagen stimmen mit der ursprünglich eingereichten Fassung der auf dem nächsten Blatt bezeichneten europäischen Patentanmeldung überein.

The attached documents are exact copies of the European patent application described on the following page, as originally filed.

Les documents fixés à cette attestation sont conformes à la version initialement déposée de la demande de brevet européen spécifiée à la page suivante.

Patentanmeldung Nr. | Patent application No. | Demande de brevet n°

03030030.5

Der Präsident des Europäischen Patentamts;
Im Auftrag

For the President of the European Patent Office

Le Président de l'Office européen des brevets
p.o.

R C van Dijk

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Anmelder/Applicant(s)/Demandeur(s):

NCTEngineering GmbH
Otto-Hahn-Strasse 24
85521 Ottobrunn
ALLEMAGNE

Bezeichnung der Erfindung/Title of the invention/Titre de l'invention:
(Falls die Bezeichnung der Erfindung nicht angegeben ist, siehe Beschreibung.
If no title is shown please refer to the description.
Si aucun titre n'est indiqué se referer à la description.)

PCM-encoded torque sensing technology

In Anspruch genommene Prioriät(en) / Priority(ies) claimed /Priorité(s) revendiquée(s)
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■ MAIWALD PATENTANWALTS GMBH

München · Hamburg · Düsseldorf
New York

Patentanwälte
Dr. Walter Maiwald (München)
Dr. Volker Hamm (Hamburg)
Dr. Stefan Michalski (Düsseldorf)
Dr. Regina Neuefeind (München)
Dipl.-Ing. Udo Preuss (München)
Dipl.-Ing. Korbinian Kopf, M.A. (München)
Dr. Norbert Hansen (München)
Dipl.-Ing. Lutz Kietzmann LL.M. (Düsseldorf)
Dr. Martin Huenges (München)
Dr. Holger Glas (München)
Dr. Vera Tiefbrunner (München)
Dr. Sigrid von Krosigk (Hamburg)

Rechtsanwälte
Stephan N. Schneller (München)
Matthias Gottschalk, MBA (München)

In Kooperation mit:
Maiwald Inc.,
European IP Services, New York
Dipl.-Ing. Korbinian Kopf, M.A.
U.S. Patent Agent

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NCT-Engineering GmbH

Otto-Hahn-Straße 24, 85521 Ottobrunn, Deutschland

PCM-Encoded Torque Sensing Technology

Field of the Invention

The magnetic principle based mechanical-stress sensing technology allows to design and to produce a wide range of “physical-parameter-sensors” (like Force Sensing, Torque Sensing, and Material Diagnostic Analysis) that can be applied where Ferro-Magnetic materials are used. The most common technologies used to build “magnetic-principle-based” sensors are:

KK:pl

Postfach 330523 · 80065 München · Elisenhof · Elisenstrasse 3 · 80335 München
Tel. +49 (0)89 74 72 660 · Fax +49 (0)89 77 64 24 · http://www.maiwald.de · info@maiwald.de
Geschäftsführer: Dr. W. Maiwald · Dr. V. Hamm · Dr. S. Michalski · Dr. R. Neuefeind · Dipl.-Ing. U. Preuss · Dipl.-Ing. L. Kietzmann · HRB Nr. 111307
Kooperation mit: Dr. Schmidt-Felzmann & Kozianka Rechtsanwälte (Hamburg)
Parr · Tauche · Leutheusser-Schnarrenberger Rechtsanwälte (München · Starnberg)

Inductive differential displacement measurement (requires torsion shaft), Measuring the changes of the materials permeability, and measuring the magnetostriction effects.

Over the last 20 years a number of different companies have developed their own and very specific solution in how to design and how to produce a magnetic principle based torque sensor (i.e. ABB, FAST, Frauenhofer Institute, FT, Kubota, MDI, NCTE, RM, Siemens, and others). These technologies are at various development stages and differ in "how-it-works", the achievable performance, the systems reliability, and the manufacturing / system cost.

Some of these technologies require that mechanical changes are made to the shaft where torque should be measured (chevrons), or rely on the mechanical torsion effect (require a long shaft that twists under torque), or that something will be attached to the shaft itself (press-fitting a ring of certain properties to the shaft surface,), or coating of the shaft surface with a special substance. No-one has yet mastered a high-volume manufacturing process that can be applied to (almost) any shaft size, achieving tight performance tolerances, and is not based on already existing technology patents.

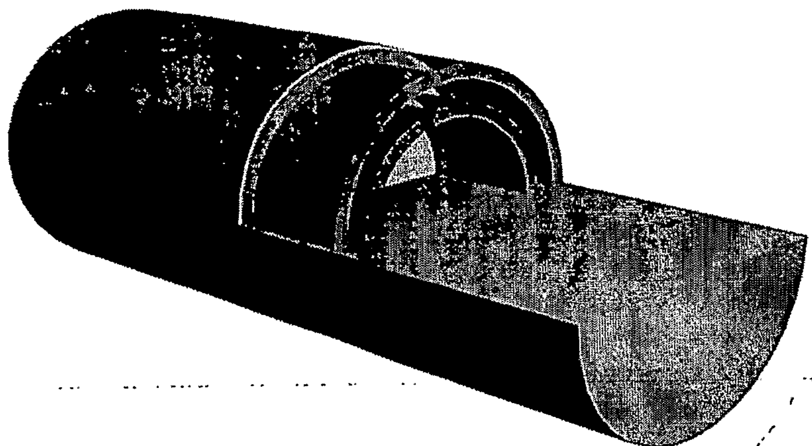
Summary of the Invention and Exemplary embodiments of the present invention

In the following, exemplary embodiments of the present invention relating to a magnetostriction principle based ***Non-Contact-Torque*** (NCT) Sensing Technology are described that offer to the user a whole host of new features and improved performances, previously not available. This technology enables the realization of a fully-integrated (small in space), real-time (high signal bandwidth) torque measurement, which is reliable and can be produced at an affordable cost, at any desired quantities. This technology is called: ***PCME*** (for Pulse-Current-Modulated Encoding) or Magnetostriction Transversal Torque Sensor.

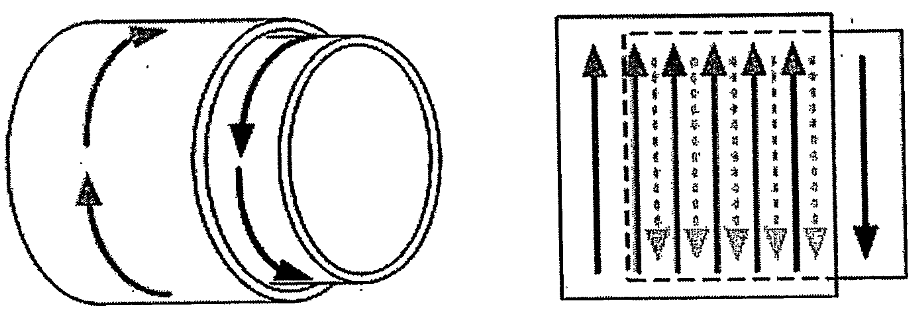
The PCME technology can be applied to the shaft without making any mechanical changes to the shaft, or without attaching anything to the shaft. Most important, the PCME technology can be applied to any shaft diameter (most other technologies have here a limitation) and does not need to rotate / spin the shaft during the encoding process (very simple and low-cost manufacturing process) which makes this technology very applicable for high-volume application.

Magnetic Field Structure (Sensor Principle)

The sensor life-time depends on a "closed-loop" magnetic field design. The PCME technology is based on two magnetic field structures, stored above each other, and running in opposite directions. When no torque stress is applied to the shaft (also called Sensor Host, or SH) then the SH will act magnetically neutral (no magnetic field can be sensed at the outside of the SH).

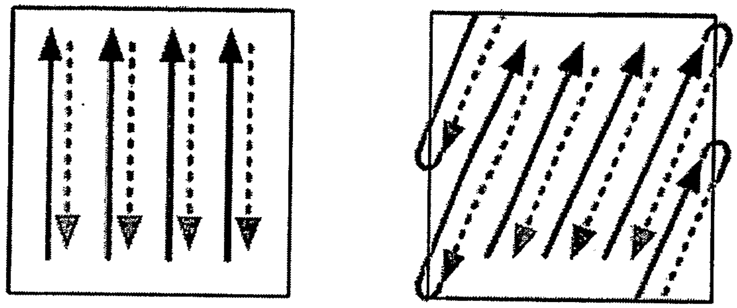


Picture: The picture shows an exemplary embodiment of the present invention where two magnetic fields are stored in the SH and running in endless circles. The outer field runs in one direction, while the inner field runs in the opposite direction.



Drawing: The PCME sensing technology uses two Counter-Circular magnetic field loops that are stored on top of each other (Picky-Back mode).

When mechanical stress (like torque) is applied at both ends of the PCME magnetized SH (Sensor Host, or Shaft) then the magnetic flux lines of both magnetic structures (or loops) will tilt in proportion to the applied torque.

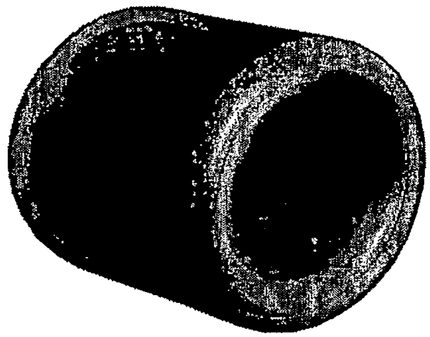


Drawing: When no mechanical stresses are applied to the SH the magnetic flux lines are running in its original path. When mechanical tresses are applied the magnetic flux lines tilt in proportion to the applied stress (like torque).

Depending on the applied torque direction (clockwise or anti-clockwise, in relation to the SH) the magnetic flux lines will either tilt to the right or tilt to the left. Where the magnetic flux lines reach the boundary of the magnetically encoded region, the magnetic flux lines from the upper layer will join-up with the magnetic flux lines from the lower layer and visa-versa. This will then form a perfectly controlled toroidal shape.

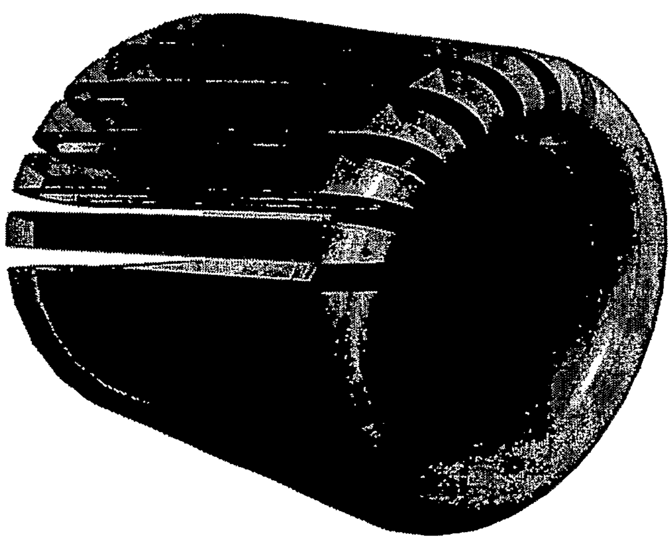
The benefits of such a magnetic structure are:

- ☐ Reduced (almost eliminated) parasitic magnetic field structures when mechanical stress is applied to the SH (this will result in better RSU performances).
- ☐ Higher Sensor-Output Signal-Slope as there are two "active" layers that compliment each other when generating a mechanical stress related signal. Explanation: When using a single-layer sensor design, the "tilted" magnetic flux lines that exit at the encoding region boundary have to create a "return passage" from one boundary side to the other. This effort effects how much signal is available to be sensed and measured outside of the SH with the secondary sensor unit.
- ☐ There are almost no limitations on the SH (shaft) dimensions where the PCME technology will be applied to. The dual layered magnetic field structure can be adapted to any solid or hollow shaft dimensions.
- ☐ The physical dimensions and sensor performances are in a very wide range programmable and therefore can be tailored to the targeted application.
- ☐ This sensor design allows to measure mechanical stresses coming from all three dimensions axis, including in-line forces applied to the shaft (applicable as a load-cell). Explanation: Earlier magnetostriction sensor designs (for example from FAST Technology) have been limited to be sensitive in 2 dimensional axis only, and could not measure in-line forces.



Picture: When torque is applied to the SH, the magnetic flux lines from both Counter-Circular magnetic loops are connecting to each other at the sensor region boundaries.

When mechanical torque stress is applied to the SH then the magnetic field will no longer run around in circles but tilt slightly in proportion to the applied torque stress. This will cause the magnetic field lines from one layer to connect to the magnetic field lines in the other layer, and with this form a toroidal shape.



Picture: An exaggerated presentation of how the magnetic flux line will form an angled toroidal structure when high levels of torque are applied to the SH.

Features and Benefits of the PCM-Encoding (PCME) Process

The magnetostriction NCT sensing technology from NCTE according to the present invention offers high performance torque sensing features like:

- ☐ No mechanical changes required on the Sensor Host (already existing shafts can be used as they are)
- ☐ Nothing will be attached to the Sensor Host (therefore nothing can fall off or change over the shaft-lifetime = high MTBF)
- ☐ During measurement the SH can rotate at any desired speed (no limitations on rpm)
- ☐ Very good RSU (Rotational Signal Uniformity) performances
- ☐ Excellent measurement linearity (up to 0.01% of FS)
- ☐ High measurement repeatability
- ☐ Very high signal resolution (better than 14 bit)
- ☐ Very high signal bandwidth (better than 10 kHz)

Depending on the chosen type of magnetostriction sensing technology, and the chosen physical sensor design, the mechanical power transmitting shaft (also called "Sensor Host" or in short "SH") can be used "as is" without making any mechanical changes to it or without attaching anything to the shaft. This is then called a "true" Non-Contact-Torque measurement principle allowing the shaft to rotate freely at any desired speed in both directions.

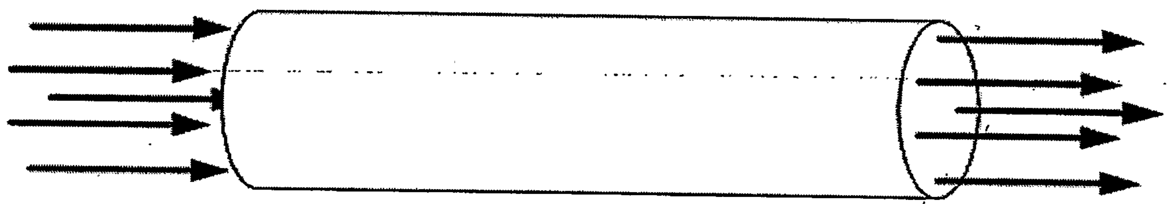
The here described PCM-Encoding (PCME) manufacturing process according to an exemplary embodiment of the present invention provides additional features no other magnetostriction technology can offer (*Uniqueness of this technology*):

- ☐ More then three times signal strength in comparison to alternative magnetostriction encoding processes (like the "RS" process from FAST).
- ☐ Easy and simple shaft loading process (high manufacturing through-putt).
- ☐ No moving components during magnetic encoding process (low complexity manufacturing equipment = high MTBF, and lower cost).
- ☐ Process allows NCT sensor to be "fine-tuning" to achieve target accuracy of a fraction of one percent.
- ☐ Manufacturing process allows shaft "pre-processing" and "post-processing" in the same process cycle (high manufacturing through-putt).
- ☐ Sensing technology and manufacturing process is ratio-metric and therefore is applicable to all shaft or tube diameters.
- ☐ The PCM-Encoding process can be applied while the SH is already assembled (depending on accessibility) (maintenance friendly).
- ☐ Final sensor is insensitive to axial shaft movements (the actual allowable axial shaft movement depends on the physical "length" of the magnetically encoded region).

- ☐ Magnetically encoded SH remains neutral and has little to non magnetic field when no forces (like torque) are applied to the SH.
- ☐ Sensitive to mechanical forces in all three dimensional axis.

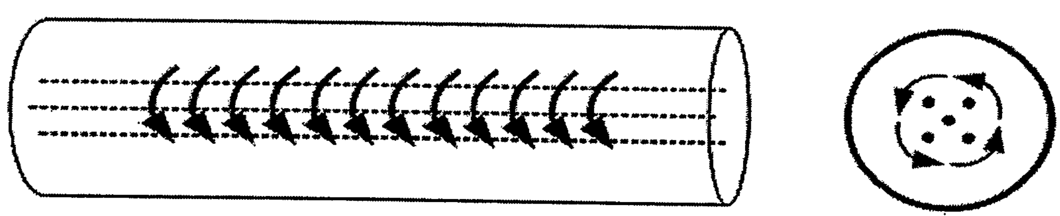
Magnetic Flux Distribution in the SH

The PCME processing technology is based on using electrical currents, passing through the SH (Sensor Host or Shaft) to achieve the desired, permanent magnetic encoding of the Ferro-magnetic material. To achieve the desired sensor performance and features a very specific and well controlled electrical current is required. Early experiments that used DC currents failed because of luck of understanding how small amounts and large amounts of DC electric current are traveling through a conductor (in this case the "conductor" is the mechanical power transmitting shaft, also called Sensor Host or in short "SH").



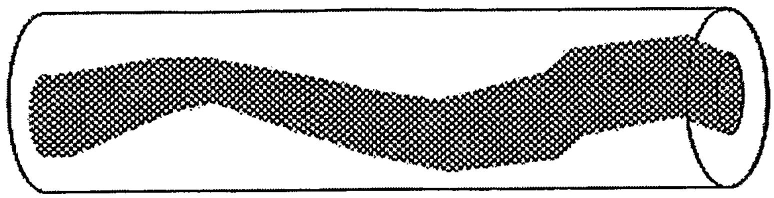
Drawing: Assumed electrical current density in a conductor

It is widely assumed that the electric current density in a conductor is evenly distributed over the entire cross-section of the conductor when an electric current (DC) passes through the conductor.



Drawing: Small electrical current forming magnetic field that ties current path in a conductor.

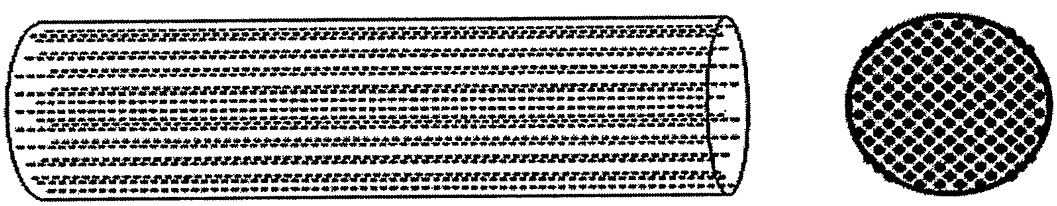
It is our experience that when a small amount of electrical current (DC) is passing through the conductor that the current density is highest at the center of the conductor. The two main reasons for this are: The electric current passing through a conductor generates a magnetic field that is tying together the current path in the center of the conductor, and the impedance is the lowest in the center of the conductor.



Drawing: Typical flow of small electrical currents in a conductor

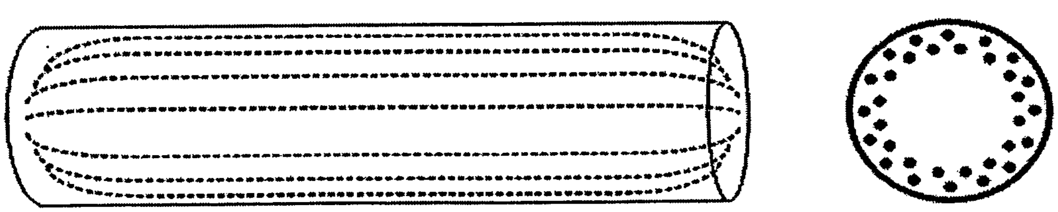
In reality, however, the electric current may not flow in a "straight" line from one connection pole to the other (similar to the shape of electric lightening in the sky).

At a certain level of electric current the generated magnetic field is large enough to cause a permanent magnetization of the Ferro-magnetic shaft material. As the electric current is flowing near or at the center of the SH, the permanently stored magnetic field will reside at the same location: near or at the center of the SH. When now applying mechanical torque to the shaft then shaft internally stored magnetic field will respond by tilting its magnetic flux path in accordance to the applied mechanical force. As the permanently stored magnetic field lies deep below the shaft surface the measurable effects are very small, not uniform and therefore not sufficient to build a reliable NCT sensor system.



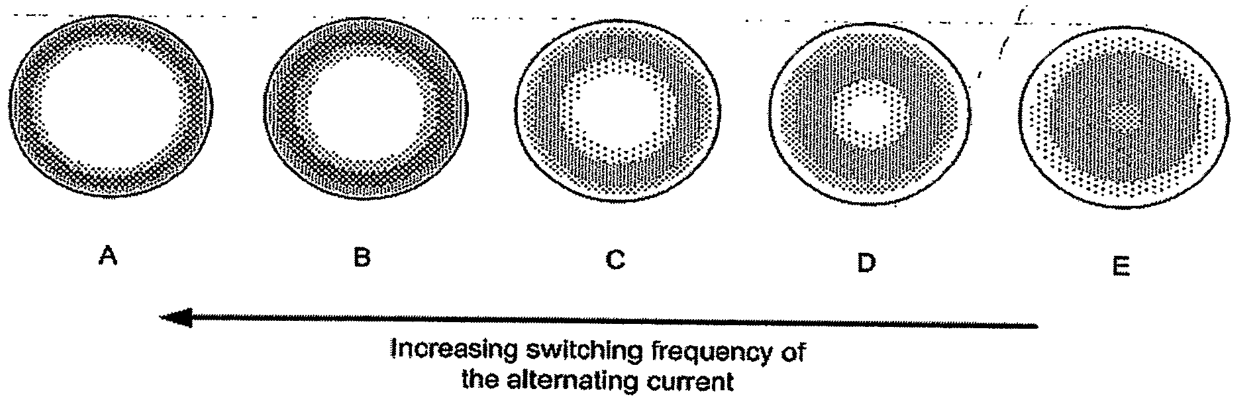
Drawing: Uniform current density in a conductor at saturation level.

Only at the saturation level is the electric current density (when applying DC) evenly distributed at the entire cross section of the conductor. The amount of electrical current to achieve this saturation level is extremely high and is mainly influenced by the cross section and conductivity (impedance) of the used conductor.



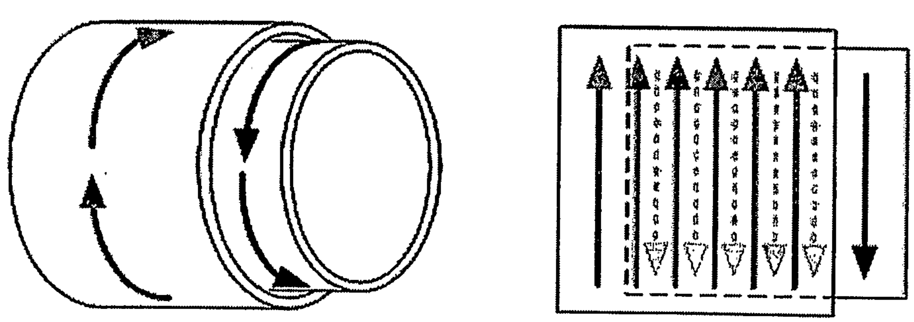
Drawing: Electric current traveling beneath or at the surface of the conductor (Skin-Effect).

It is also widely assumed that when passing through alternating current (like a radio frequency signal) through a conductor that the signal is passing through the skin layers of the conductor, called the Skin Effect. The chosen frequency of the alternating current defines the "Location / position" and "depth" of the Skin Effect. At high frequencies the electrical current will travel right at or near the surface of the conductor (A) while at lower frequencies (in the 5 to 10 Hz regions for a 20 mm diameter SH) the electrical alternating current will penetrate more the center of the shafts cross section (E). Also, the relative current density is higher in the current occupied regions at higher AC frequencies in comparison to the relative current density near the center of the shaft at very low AC frequencies (as there is more space available for the current to flow through).



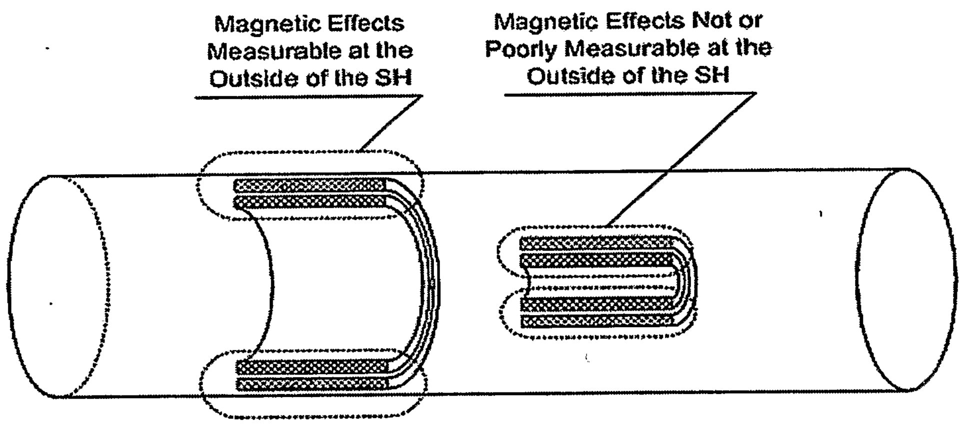
Drawing: The electrical current density of an electrical conductor (cross-section 90 deg to the current flow) when passing through the conductor an alternating current at different frequencies.

The desired magnetic field design of the PCME sensor technology are two circular magnetic field structures, stored in two layers on top of each other ("Picky-Back"), and running in opposite direction to each other (Counter-Circular).



Drawing: Desired magnetic sensor structure: two endless magnetic loops placed on top of each other, running in opposite directions to each other: Counter-Circular "Picky-Back" Field Design.

To make this magnetic field design highly sensitive to mechanical stresses that will be applied to the SH (shaft), and to generate the largest sensor signal possible, the desired magnetic field structure has to be placed nearest to the shaft surface. Placing the circular magnetic fields to close to the center of the SH will cause damping of the user available sensor-output-signal slope (most of the sensor signal will travel through the Ferro-magnetic shaft material as it has a much higher permeability in comparison to air), and increases the non-uniformity of the sensor signal (in relation to shaft rotation and to axial movements of the shaft in relation to the secondary sensor.



Drawing: Magnetic field structures stored near the shaft surface and stored near the center of the shaft.

It may be difficult to achieve the desired permanent magnetic encoding of the SH when using AC (alternating current) as the polarity of the created magnetic field is constantly changing and therefore may act more as a Degaussing system.

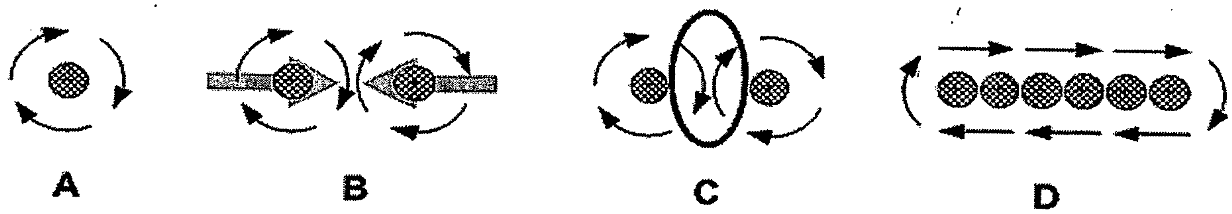
The PCME technology requires that a strong electrical current ("uni-polar" or DC, to prevent erasing of the desired magnetic field structure) is traveling right below the shaft surface (to ensure that the sensor signal will be uniform and measurable at the outside of the shaft). In addition a Counter-Circular, "picky back" magnetic field structure needs to be formed.

It is possible to place the two Counter-Circular magnetic field structures in the shaft by storing them into the shaft one after each other. First the inner layer will be stored in the SH, and then the outer layer by using a weaker magnetic force (preventing that the inner layer will

be neutralized and deleted by accident. To achieve this, the known "permanent" magnet encoding techniques can be applied as described in patents from FAST technology, or by using a combination of electrical current encoding and the "permanent" magnet encoding.

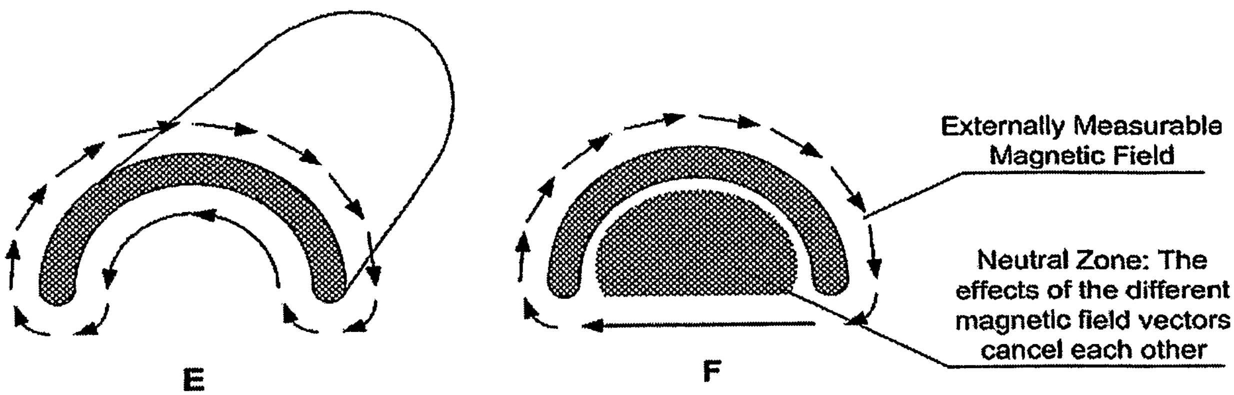
A much simpler and faster encoding process uses "only" electric current to achieve the desired Counter-Circular "Picky-Back" magnetic field structure. The most challenging part here is to generate the Counter-Circular magnetic field.

A uniform electrical current will produce a uniform magnetic field, running around the electrical conductor in a 90 deg angle, in relation to the current direction (A). When placing two conductors side-by-side (B) then the magnetic field between the two conductors seems to cancel-out the effect of each other (C). Although still present, there is no detectable (or measurable) magnetic field between the closely placed two conductors. When placing a number of electrical conductors side-by-side (D) the "measurable" magnetic field seems to go around the outside the surface of the "flat" shaped conductor.



Drawing: The magnetic effects when looking at the cross-section of a conductor with a uniform current flowing through them.

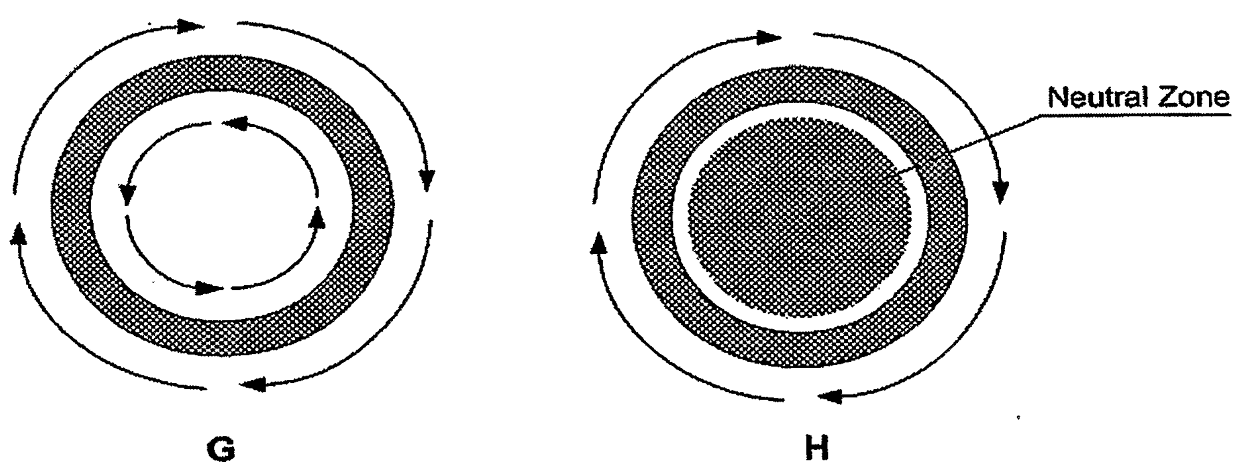
The "flat" or rectangle shaped conductor has now been bent into a "U"-shape. When passing an electrical current through the "U"-shaped conductor then the magnetic field following the outer dimensions of the "U"-shape is canceling out the measurable effects in the inner halve of the "U".



Drawing: The zone inside the "U"-shaped conductor seem to be magnetically "Neutral" when an electrical current is flowing through the conductor.

When no mechanical stress is applied to the cross-section of a "U"-shaped conductor it seems that there is no magnetic field present inside of the "U" (F). But when bending or twisting the "U"-shaped conductor the magnetic field will no longer follow its original path (90 deg angle to the current flow). Depending on the applied mechanical forces, the magnetic field begins to change slightly its path. At that time the magnetic-field-vector that is caused by the mechanical stress can be sensed and measured at the surface of the conductor, inside and outside of the "U"-shape. Note: This phenomena is applies only at very specific electrical current levels.

The same applies to the "O"-shaped conductor design. When passing a uniform electrical current through an "O"-shaped conductor (Tube) the measurable magnetic effects inside of the "O" (Tube) have canceled-out each other (G).



Drawing: The zone inside the "O"-shaped conductor seem to be magnetically "Neutral" when an electrical current is flowing through the conductor.

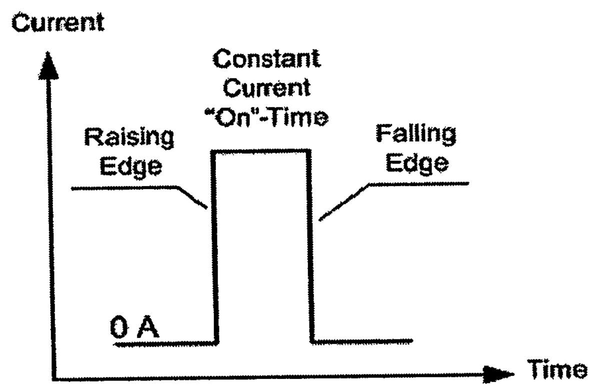
However, when mechanical stresses are applied to the "O"-shaped conductor (Tube) it becomes evident that there has been a magnetic field present at the inner side of the "O"-shaped conductor. The inner, counter directional magnetic field (as well as the outer magnetic field) begins to tilt in relation to the applied torque stresses. This tilting field can be clearly sensed and measured.

Encoding Pulse Design

To achieve the desired magnetic field structure (Counter-Circular, Picky-Back, Fields Design) inside the SH, according to an exemplary embodiment of a method of the present invention, unipolar electrical current pulses are passed through the Shaft (or SH). By using "pulses" the desired "Skin-Effect" can be achieved. By using a "unipolar" current direction (not changing the direction of the electrical current) the generated magnetic effect will not be erased accidentally.

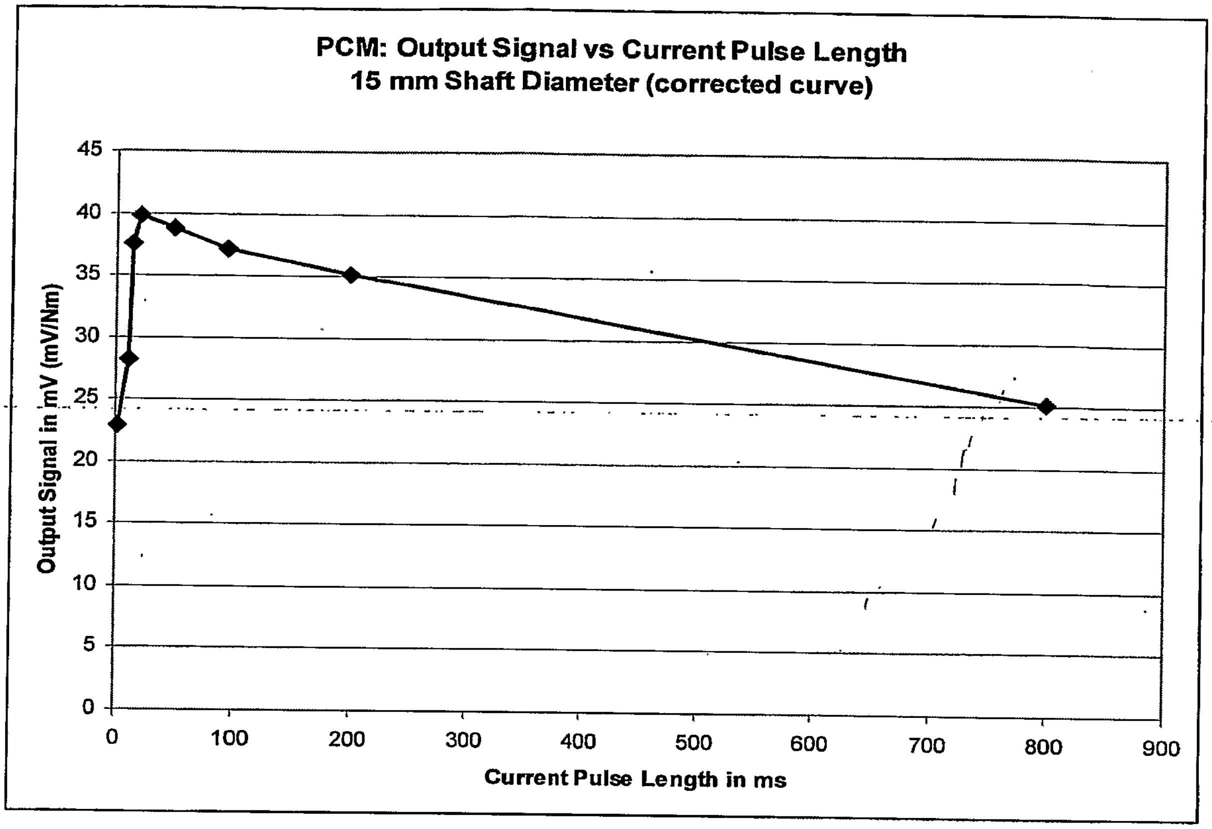
The used current pulse shape is most critical to achieve the desired PCME sensor design. Each parameter has to be accurately and repeatable controlled: Current raising time, Constant current on-time, Maximal current amplitude, and Current falling time. In addition it is very critical that the current enters and exits very uniformly around the entire shaft surface.

Rectangle Current Pulse Shape



Graph: Rectangle shaped electrical current pulse

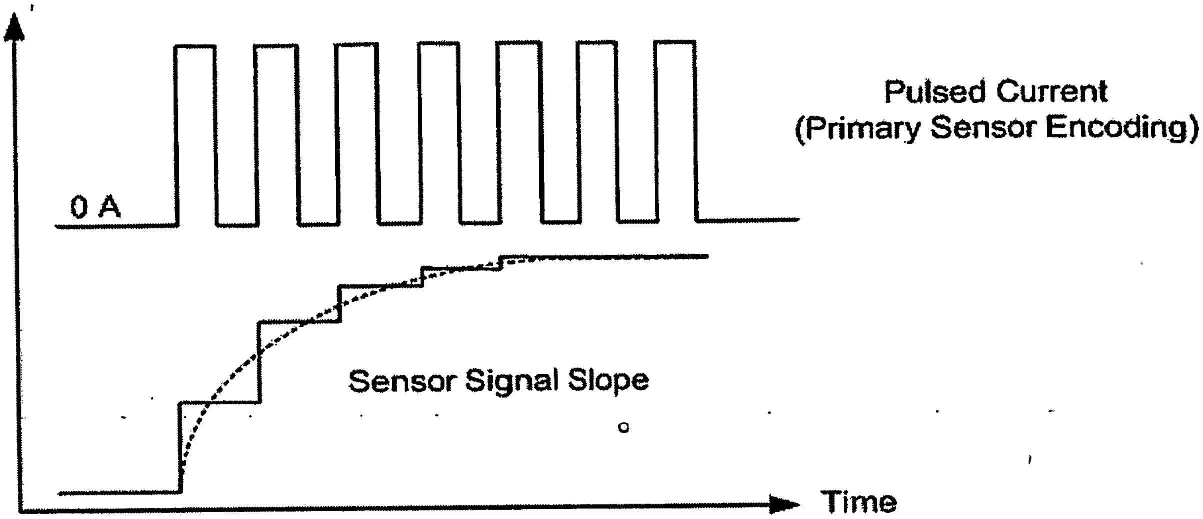
A rectangle shaped current pulse has a fast raising positive edge and a fast falling current edge. When passing a rectangle shaped current pulse through the SH, the raising edge is responsible for forming the targeted magnetic structure of the PCME sensor while the flat "on" time and the falling edge of the rectangle shaped current pulse are counter productive.



Graph: Relationship between rectangles shaped Current Encoding Pulse-Width (Constant Current On-Time) and Sensor Output Signal Slope.

In the following example a rectangle shaped current pulse has been used to generate and store the Couter-Circilar "Picky-Back" field in a 15 mm diameter, 14CrNi14 shaft. The pulsed electric current had its maximum at around 270 Ampere. The pulse "on-time" has been electronically controlled. Because of the high frequency component in the rising and falling edge of the encoding pulse, this experiment can not truly represent the effects of a true DC encoding SH. Therefore the Sensor-Output-Signal Slope-curve eventually flattens-out at above 20 mV/Nm when passing the Constant-Current On-Time of 1000 ms.

Without using a fast raising current-pulse edge (like using a controlled ramping slope) the sensor output signal slope would have been very poor (below 10 mV/Nm). Note: In this experiment (using 14CrNi14) the signal hysteresis was around 0.95% of the FS signal (FS = 75 Nm torque).

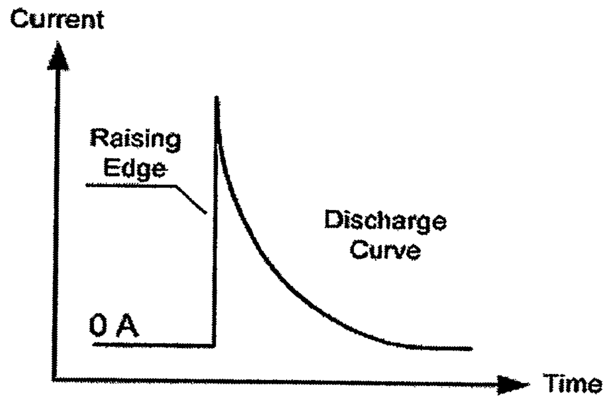


Graph: Increasing the Sensor-Output Signal-Slope by using several rectangle shaped current pulses in succession.

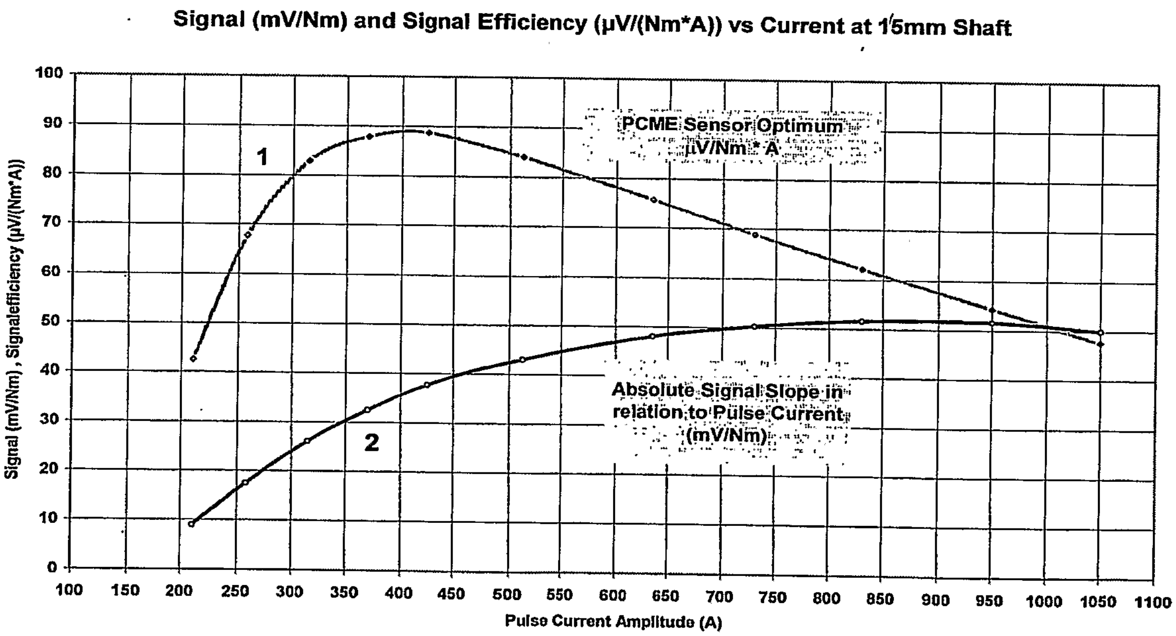
The Sensor-Output-Signal slope can be improved when using several rectangle shaped current-encoding-pulses in successions. In comparisons to other encoding-pulse-shapes the fast falling current-pulse signal slope of the rectangle shaped current pulse will prevent that the Sensor-Output-Signal slope may ever reach an optimal performance level. Meaning that after only a few current pulses (2 to 10) have been applied to the SH (or Shaft) the Sensor-Output Signal-Slope will no longer rise.

Discharge Current Pulse Shape

The Discharge-Current-Pulse has no Constant-Current ON-Time and has no fast falling edge. Therefore the primary and most felt effect in the magnetic encoding of the SH is the fast raising edge of this current pulse type.



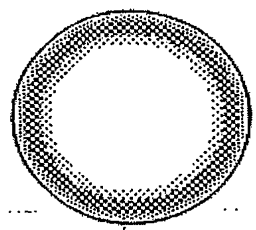
Graph: Sharp raising current edge and a typical discharging curve provides best results when creating a PCME sensor.



Graph: PCME Sensor-Output Signal-Slope optimization by identifying the right pulse current.

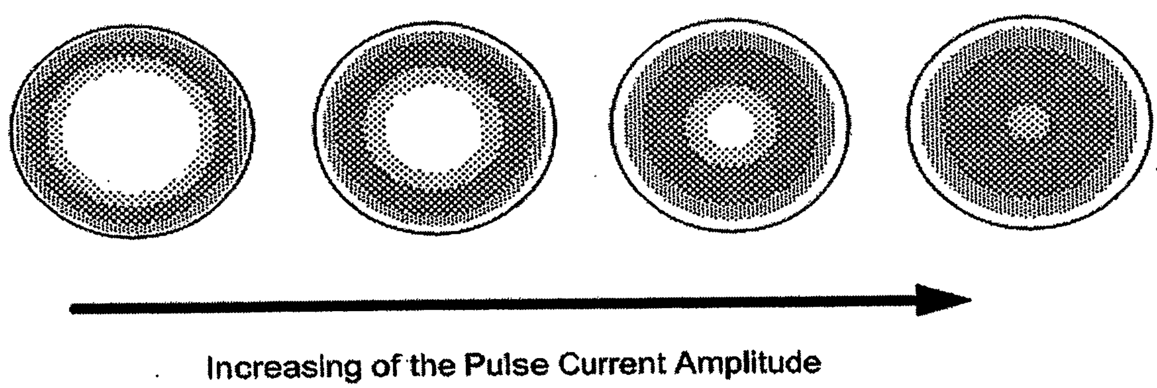
At the very low end of the pulse current scale (0 to 75 A for a 15 mm diameter shaft, 14CrNi14 shaft material) the "Discharge-Current-Pulse type is not powerful enough to cross the magnetic threshold needed to create a lasting magnetic field inside the Ferro magnetic shaft. When increasing the pulse current amplitude the double circular magnetic field

structure begins to form below the shaft surface. As the pulse current amplitude increases so does the achievable torque sensor-output signal-amplitude of the secondary sensor system. At around 400A to 425A the optimal PCME sensor design has been achieved (the two counter flowing magnetic regions have reached their most optimal distance to each other and the correct flux density for best sensor performances.



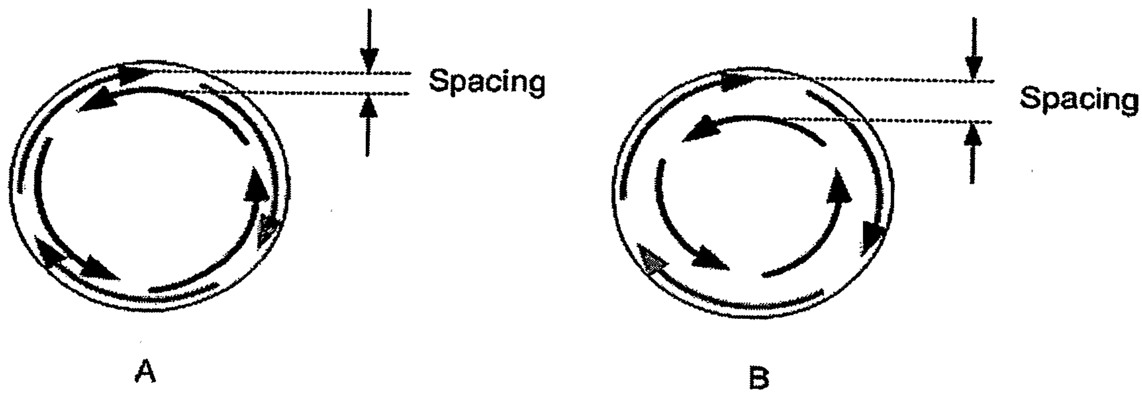
Drawing: Sensor Host (SH) cross section with the optimal PCME electrical current density and location during the encoding pulse.

When increasing further the pulse current amplitude the absolute, torque force related, sensor signal amplitude will further increase (curve 2) for some time while the overall PCME-typical sensor performances will decrease (curve 1). When passing 900A Pulse Current Amplitude (for a 15 mm diameter shaft) the absolute, torque force related, sensor signal amplitude will begin to drop as well (curve 2) while the PCME sensor performances are now very poor (curve 1).



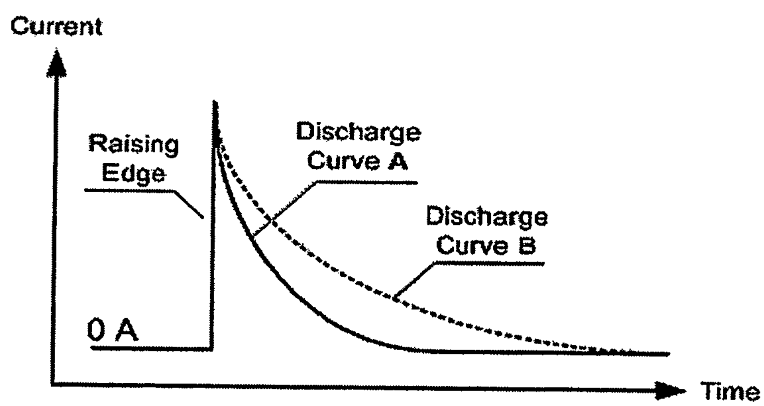
Drawing: Sensor Host (SH) cross sections and the electrical pulse current density at different and increasing pulse current levels.

As the electrical current occupies a larger cross section in the SH the spacing between the inner circular region and the outer (near the shaft surface) circular region becomes larger.



Drawing: Better PCME sensor performances will be achieved when the spacing between the Counter-Circular "Picky-Back" Field design is narrow (A).

The desired double, counter flow, circular magnetic field structure will be less able to create a close loop structure under torque forces which results in a decreasing secondary sensor signal amplitude.

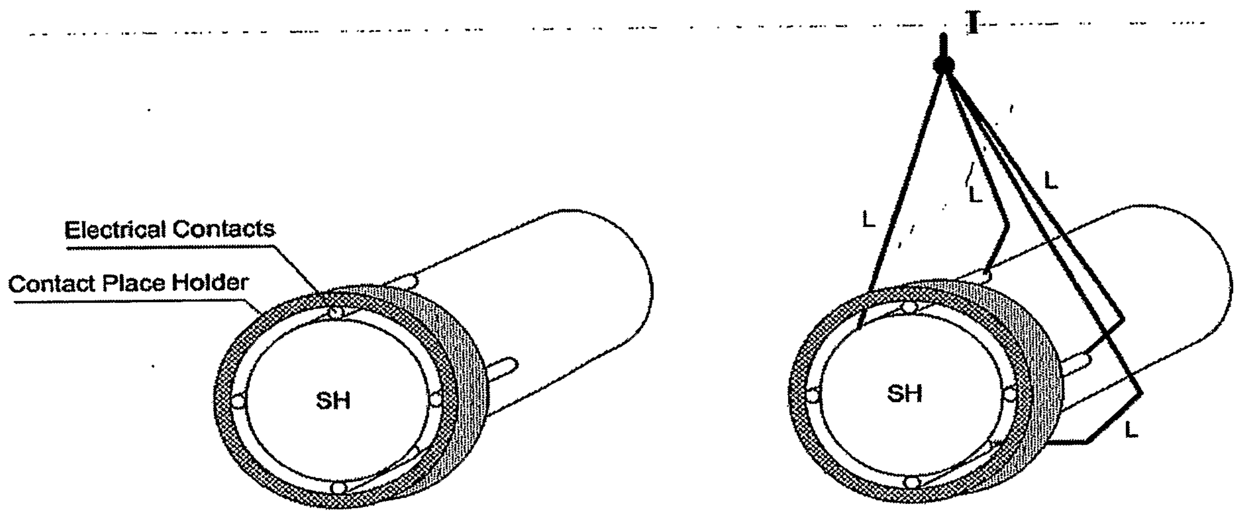


Graph: Flattening-out the current-discharge curve will also increase the Sensor-Output Signal-Slope.

When increasing the Current-Pulse discharge time (making the current pulse wider) (B) the Sensor-Output Signal-Slope will increase. However the required amount of current is very high to reduce the slope of the falling edge of the current pulse. It might be more practical to use a combination of a high current amplitude (with the optimal value) and the slowest possible discharge time to achieve the highest possible Sensor-Output Signal Slope.

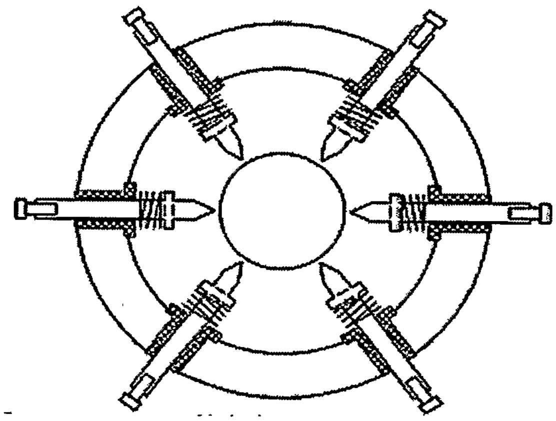
Primary Sensor Processing: Electrical Connection Devices

The PCME technology (it has to be noted that the term 'PCME' technology is used to refer to exemplary embodiments of the present invention) relies on passing through the shaft very high amounts of pulse-modulated electrical current at the location where the Primary Sensor should be produced. When the surface of the shaft is very clean and highly conductive a multi-point Cupper or Gold connection may be sufficient to achieve the desired sensor signal uniformity. Important is that the Impedance is identical of each connection point to the shaft surface. This can be best achieved when assuring the cable length (L) is identical before it joins the main current connection point (I)



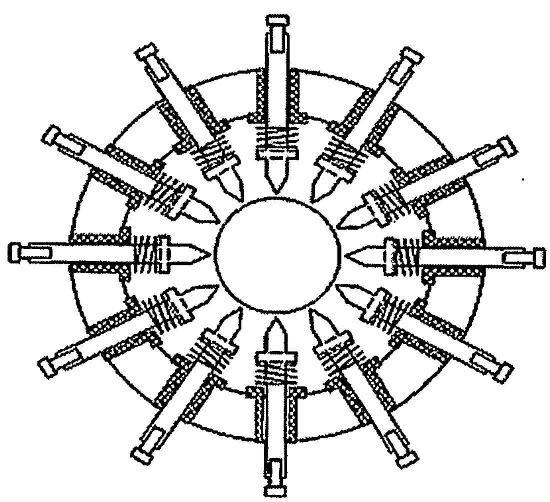
Drawing: Simple electrical multi-point connection to the shaft surface.

However, in most cases a reliable and repeatable multi-point electrical connection can be only achieved by ensuring that the impedance at each connection point is identical and constant. Using a spring pushed, sharpened connector will penetrate possible oxidation or isolation layers (maybe caused by finger prints) at the shaft surface.

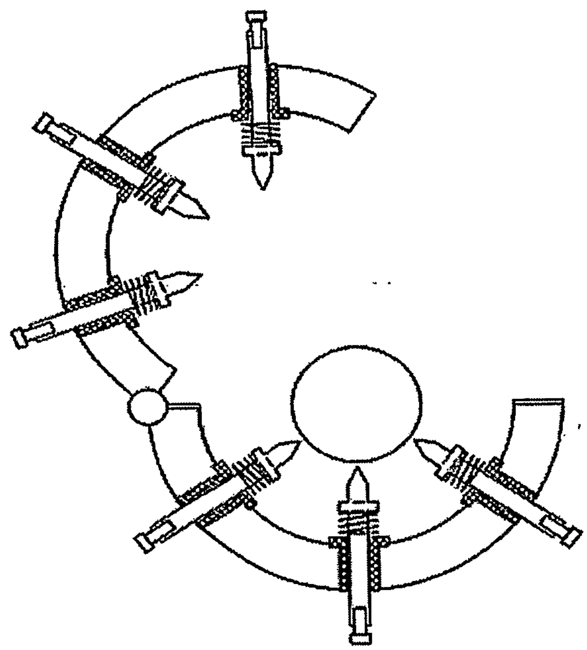


Drawing: Multi channel, electrical connecting fixture, with spring loaded contact points.

When processing the shaft it is most important that the electrical current is injected and extracted from the shaft in the most uniform way possible. The above drawing shows several electrical, from each other insulated, connectors that are held by a fixture around the shaft. This device is called a Shaft-Processing-Holding-Clamp (or SPHC). The number of electrical connectors required in a SPHC depends on the shafts outer diameter. The larger the outer diameter, the more connectors are required. The spacing between the electrical conductors has to be identical from one connecting point to the next connecting point. This method is called Symmetrical-"Spot"-Contacts.



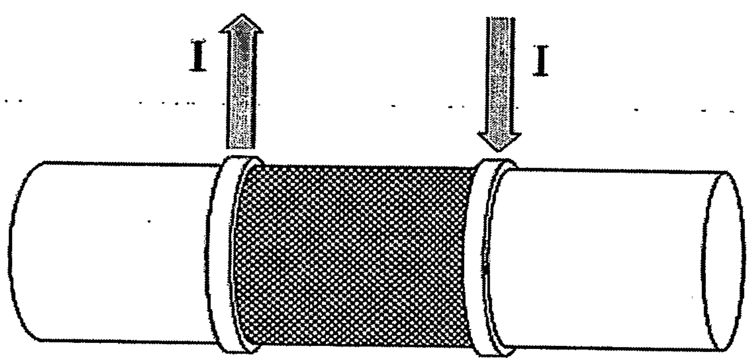
Drawing: Increasing the number of electrical connection points will assist the efforts of entering and exiting the Pulse-Modulated electrical current. It will also increase the complexity of the required electronic control system.



Drawing: Example of how to open the SPHC for easy shaft loading.

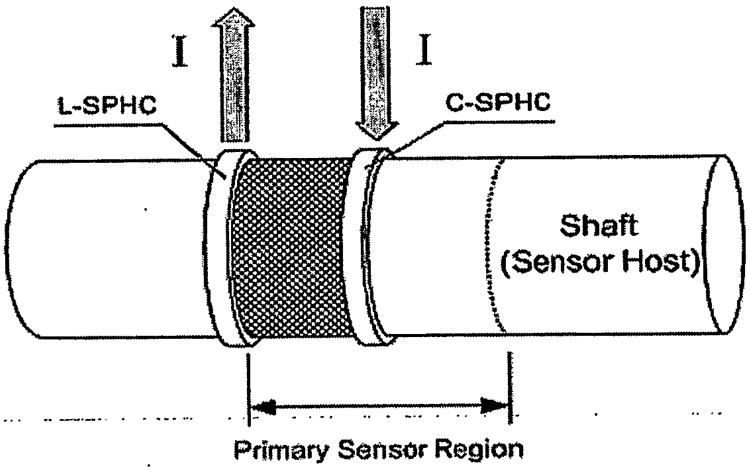
Primary Sensor Processing: Encoding

The encoding of the primary shaft can be done by using permanent magnets applied at a rotating shaft or using electric currents passing through the desired section of the shaft. When using permanent magnets a very complex, sequential procedure is necessary to put the two layers of closed loop magnetic fields, on top of each other, in the shaft. When using the PCME procedure the electric current has to enter the shaft and exit the shaft in the most symmetrical way possible to achieve the desired performances.



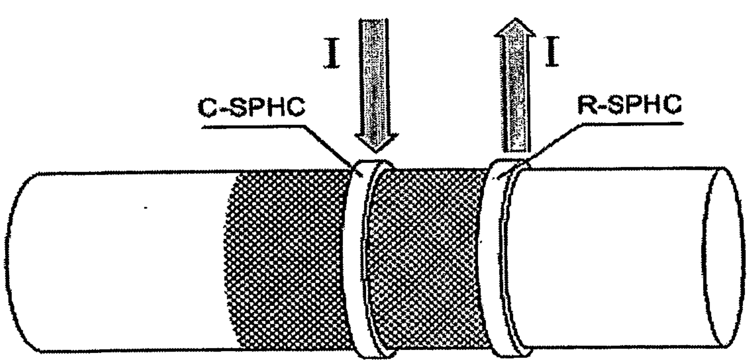
Drawing: Using two SPHCs (Shaft Processing Holding Clamps) that are placed at the borders of the planned sensing encoding region. Through one SPHC the pulsed electrical current (I) will enter the shaft, while at the second SPHC the pulsed electrical current (I) will exit the shaft. The region between the two SPHCs will then turn into the primary sensor.

This particular sensor process will produce a Single Field (SF) encoded region. One benefit of this design (in comparison to those that are described below) is that this design is insensitive to any axial shaft movements in relation to the location of the secondary sensor devices. The disadvantage of this design is that when using axial (or in-line) placed MFS coils the system will be sensitive to magnetic stray fields (like the earth magnetic field).

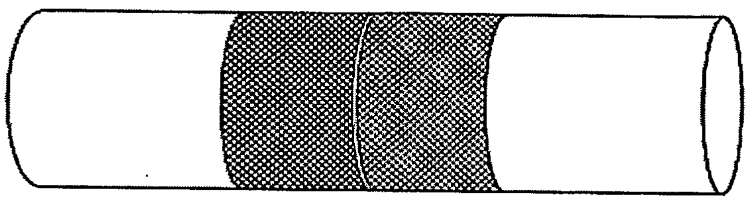


Drawing: A Dual Field (DF) encoded region (meaning two independent functioning sensor regions with opposite polarity, side-by-side) allows canceling the effects of uniform magnetic stray fields when using axial (or in-line) placed MFS coils. However, this primary sensor design also shortens the tolerable range of shaft movement in axial direction (in relation to the location of the MFS coils). There are two ways to produce a Dual Field (DF) encoded region with the PCME technology. The sequential process, where the magnetic encoded sections are produced one after each other, and the parallel process, where both magnetic encoded sections are produced at the same time.

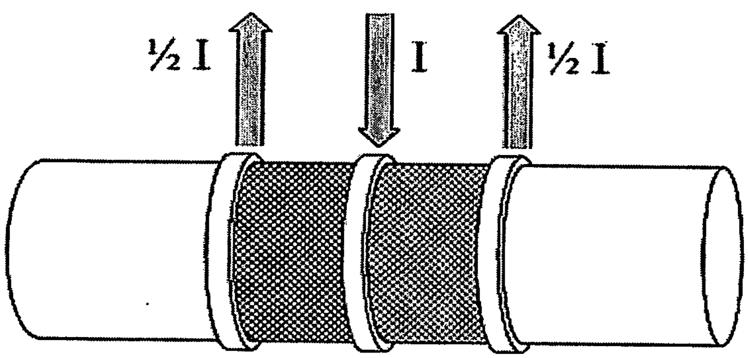
The first process step of the sequential dual field design is to magnetically encode one sensor section (identically to the Single Field procedure), whereby the spacing between the two SPHC has to be halve of the desired final length of the Primary Sensor region. To simplify the explanations of this process we call the SPHC that is placed in the center of the final Primary Sensor Region the Center SPHC (C-SPHC), and the SPHC that is located at the left side of the Center SPHC: L-SPHC.



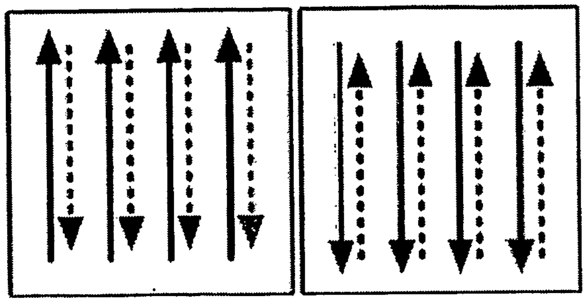
Drawing: The second process step of the sequential Dual Field encoding will use the SPHC that is located in the center of the Primary Sensor region (called C-SPHC) and a second SPHC that is placed at the other side (the right side) of the center SPHC, called R-SPHC. Important is that the current flow direction in the center SPHC (C-SPHC) is identical at both process steps.



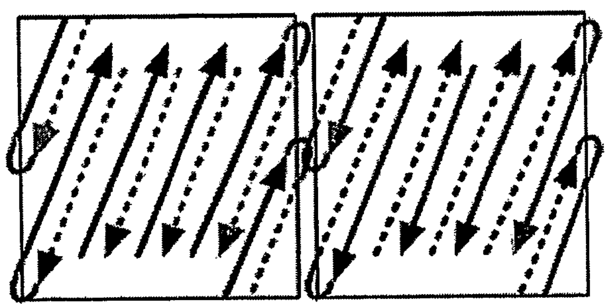
Drawing: The performance of the final Primary Sensor Region depends on how close the two encoded regions can be placed in relation to each other. And this is dependent on the design of the used center SPHC. The narrower the in-line space contact dimensions are of the C-SPHC, the better are the performances of the Dual Field PCME sensor.



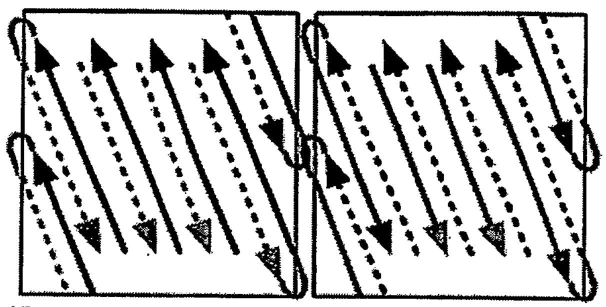
The above drawing shows the pulse application according to another exemplary embodiment of the present invention. As my be taken from the above drawing, the pulse is applied to three locations of the shaft. Due to the current distribution to both sides of the middle electrode where the current I is entered into the shaft, the current leaving the shaft at the lateral electrodes is only half the current entered at the middle electrode, namely ½ I. The electrodes are depicted as rings which dimensions are adapted to the dimensions of the outer surface of the shaft. However, it has to be noted that other electrodes may be used, such as the electrodes comprising a plurality of pin electrodes described later in this text.



Drawing: Magnetic flux directions of the two sensor sections of a Dual Field PCME sensor design when no torque is applied to the shaft. The counter flow magnetic flux loops do not interact with each other.



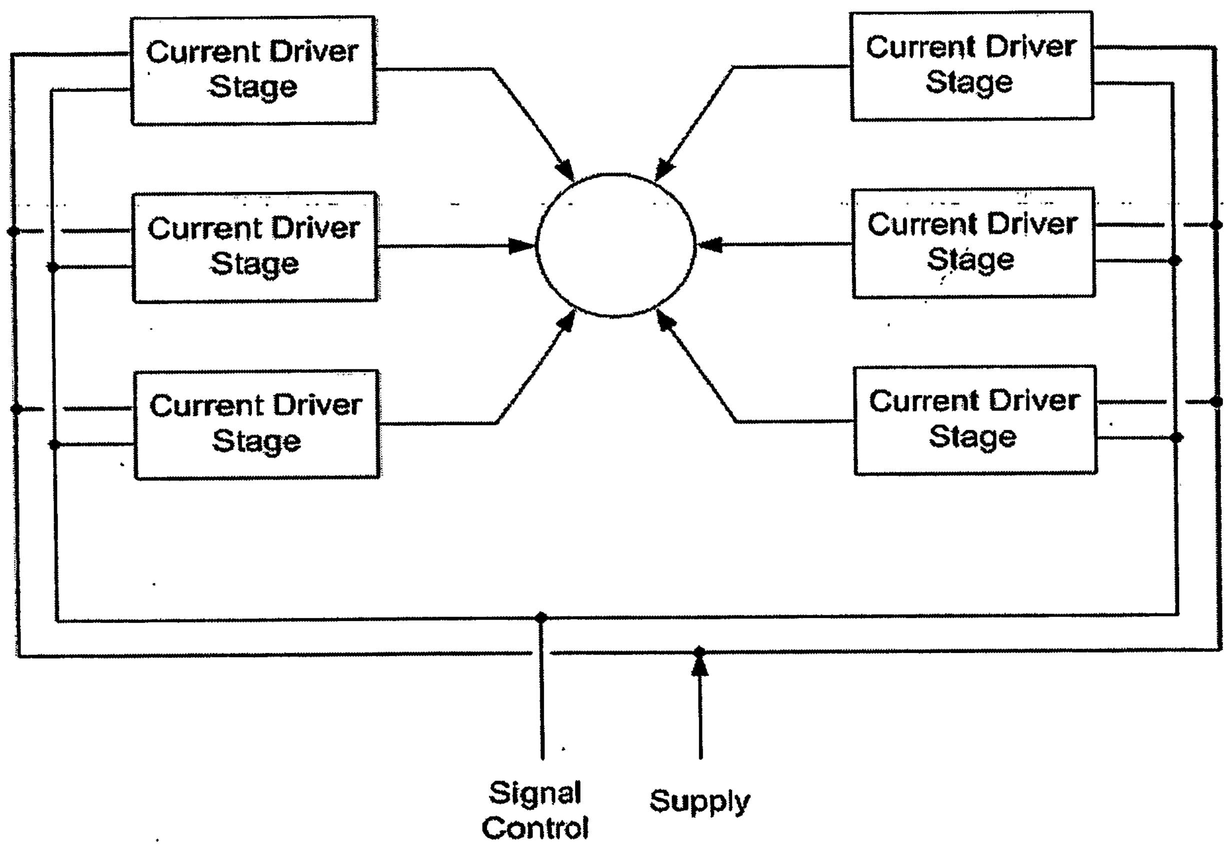
Drawing: When torque forces are applied in a particular direction then the magnetic flux loops begin to run with an increasing tilting angle inside the shaft. When the tilted magnetic flux reaches the PCME segment boundary then the flux line interacts with the counterflowing magnetic flux lines as shown above.



Drawing: When the applied torque direction is changing (for example from clock-wise to counter-clock-wise) so will change the tilting angle of the counterflow magnetic flux structures inside the PCM Encoded shaft.

Multi Channel Current Driver for Shaft Processing

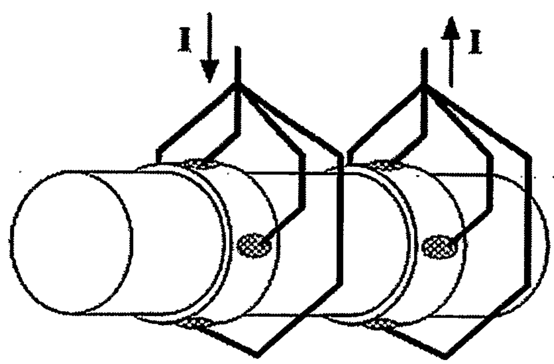
In cases where an absolute identical impedance of the current path to the shaft surface can not be guaranteed, then electric current controlled driver stages can be used to overcome this problem.



Drawing: A six-channel synchronized Pulse current driver system for small diameter Sensor Hosts (SH). As the shaft diameter increases so will the number of current driver channels.

From Bras Ring Contacts to Symmetrical "Spot" Contacts

When the shaft diameter is relative small and the shaft surface is clean and free from any oxidations at the desired Sensing Region, then a simple "Bras"-ring (or Copper-ring) contact method can be chosen to process the Primary Sensor.

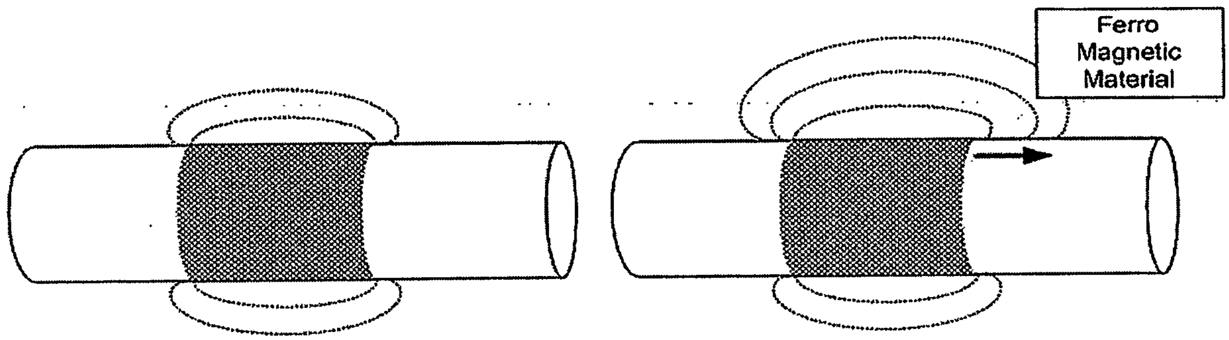


Drawing: Bras-rings (or Copper-rings) tightly fitted to the shaft surface, with solder connections for the electrical wires. The area between the two Bras-rings (Copper-rings) is the encoded region.

However, it is very likely that the achievable RSU performances are much lower then when using the Symmetrical "Spot" Contact method.

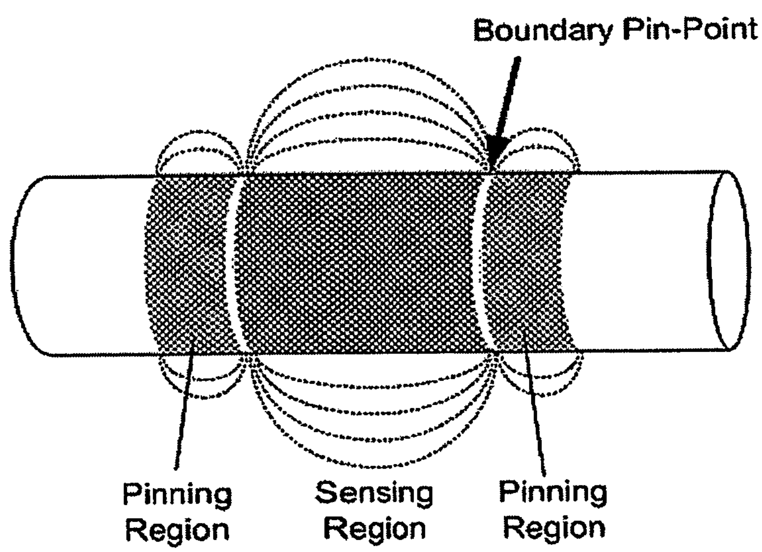
Hot-Spotting

A standard single field (SF) PCME sensor has very poor Hot-Spotting performances. The external magnetic flux profile of the SF PCME sensor segment (when torque is applied) is very sensitive to possible changes (in relation to Ferro magnetic material) in the nearby environment. As the magnetic boundaries of the SF encoded sensor segment are not well defined (not "Pinned Down") they can "extend" towards the direction where Ferro magnet material is placed near the PCME sensing region.



Drawing: A PCME process magnetized sensing region is very sensitive to Ferro magnetic materials that may come close to the boundaries of the sensing regions.

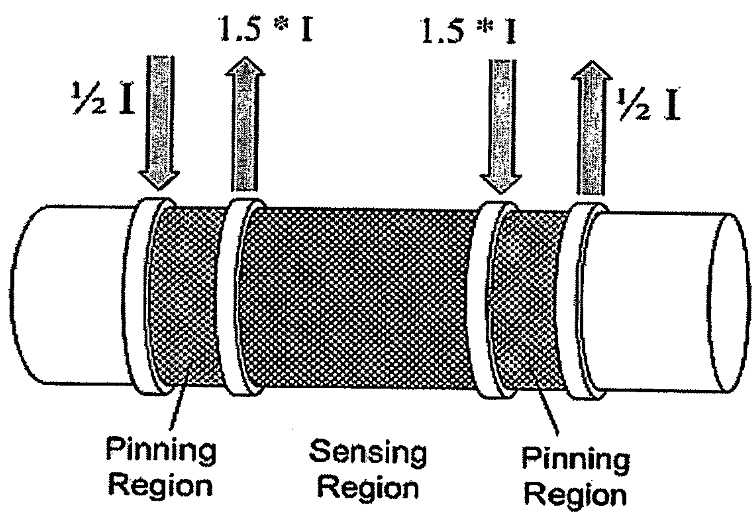
To reduce the Hot-Spotting sensor sensitivity the PCME sensor segment boundaries have to be better defined by pinning them down (they can no longer move).



Drawing: PCME processed Sensing region with two "Pinning Field Regions", one on each side of the Sensing Region.

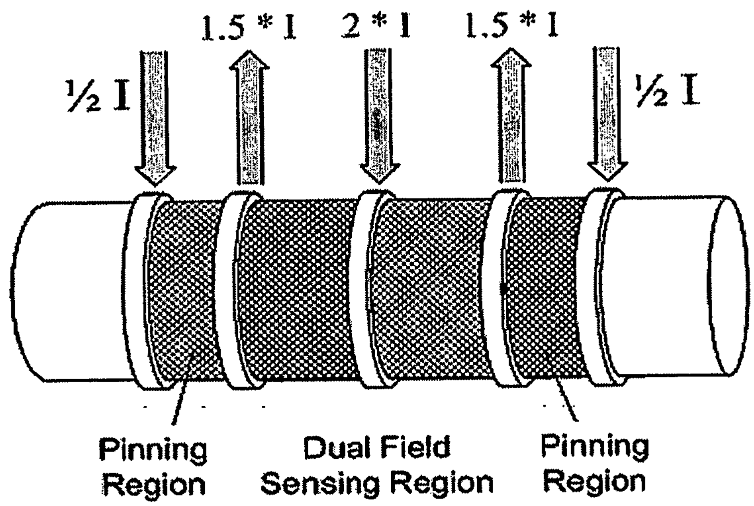
By placing Pinning Regions closely on either side the Sensing Region, the Sensing Region Boundary has been pinned down to a very specific location. When Ferro magnetic material is coming close to the Sensing Region, it may have an effect on the outer boundaries of the Pinning Regions, but it will have very limited effects on the Sensing Region Boundaries.

There are a number of different ways, according to exemplary embodiments of the present invention how the SH (Sensor Host) can be processed to get a Single Field (SF) Sensing Region and two Pinning Regions, one on each side of the Sensing Region. Either each region is processed after each other (Sequential Processing) or two or three regions are processed simultaneously (Parallel Processing). The Parallel Processing provides a more uniform sensor (reduced parasitic fields) but requires much higher levels of electrical current to get to the targeted sensor signal slope.



Drawing: Parallel Processing example for a Single Field (SF) PCME sensor with Pinning Regions on either side of the main sensing region, in order to reduce (or even eliminate) Hot-Spotting.

A Dual Field PCME Sensor is less sensitive to the effects of Hot-Spotting as the sensor center region is already Pinned-Down. However, the remaining Hot-Spotting sensitivity can be further reduced by placing Pinning Regions on either side of the Dual-Field Sensor Region.

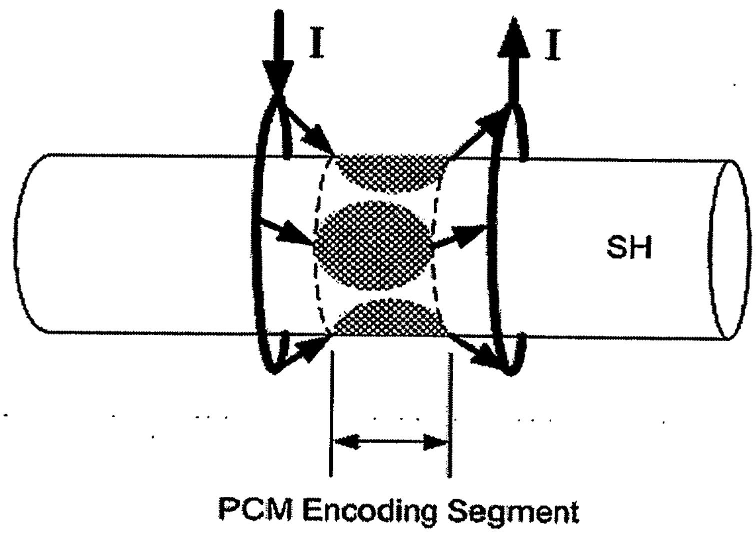


Drawing: Dual Field (DF) PCME sensor with Pinning Regions either side.

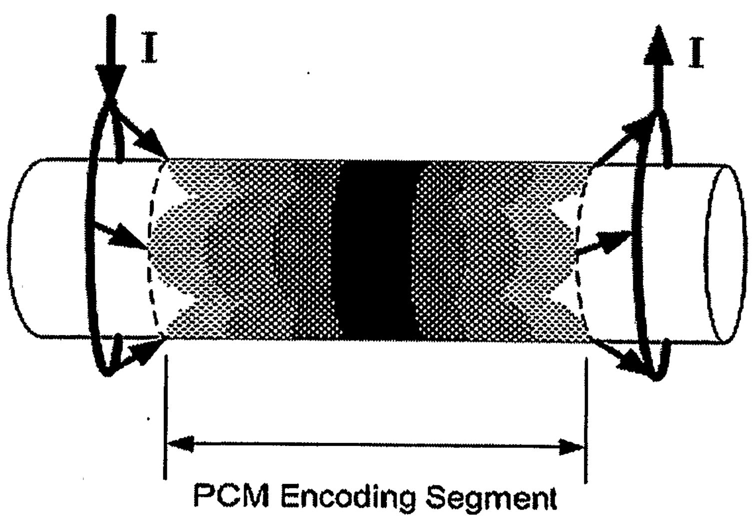
When Pinning Regions are not allowed or possible (example: limited axial spacing available) then the Sensing Region has to be magnetically shielded from the influences of external Ferro Magnetic Materials.

RSU

The RSU sensor performance are, according to current understanding, mainly depending on how circumferentially uniform the electrical current entered and exited the SH surface, and the physical space between the electrical current entry and exit points. The larger the spacing between the current entry and exit points, the better is the RSU performance.



Drawing: When the spacings between the individual circumferential placed current entry points are relatively large in relation to the shaft diameter (and equally large are the spacings between the circumferentially placed current exit points) then this will result in very poor RSU performances. In such a case the length of the PCM Encoding Segment has to be as large as possible as otherwise the created magnetic field will be circumferentially non-uniform.



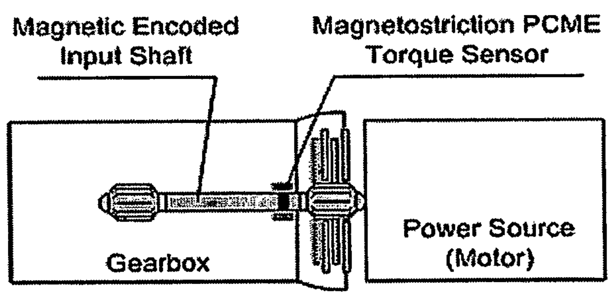
Drawing: By widening the PCM Encoding Segment the circumferentially magnetic field distribution will become more uniform (and eventually almost perfect) at the halve distance

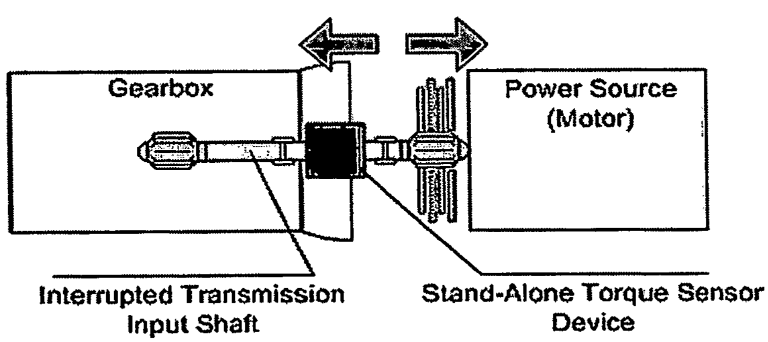
between the current entry and current exit points. Therefore the RSU performance of the PCME sensor is best at the halve way-point between of the current-entry / current-exit points.

Description of the basic design issues of a NCT sensor system

Without going into the specific details of the PCM-Encoding technology, the end-user of this sensing technology need to now some design details that will allow him to apply and to use this sensing concept in his application. The following pages describe the basic elements of a magnetostriction based NCT sensor (like the primary sensor, secondary sensor, and the SCSP electronics), what the individual components look like, and what choices need to be made when integrating this technology into an already existing product.

In principle the PCME sensing technology can be used to produce a stand-alone sensor product. However, in already existing industrial applications there is little to none space available for a "stand-alone" product. The PCME technology can be applied in an existing product without the need of redesigning the final product.

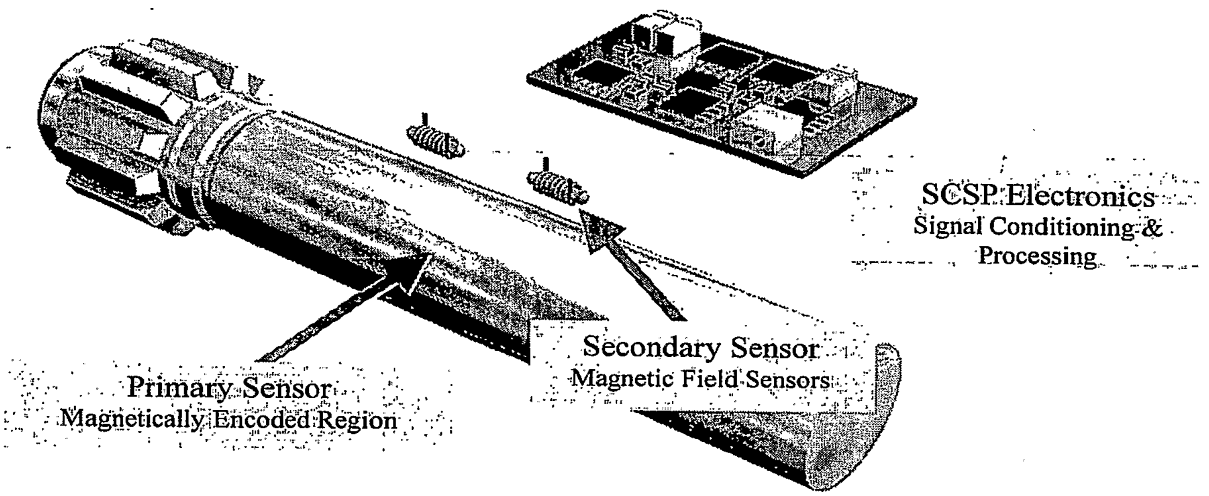




In case a stand-alone torque sensor device will be applied to a motor – transmission system it may require that the entire system need to undergo a major design change.

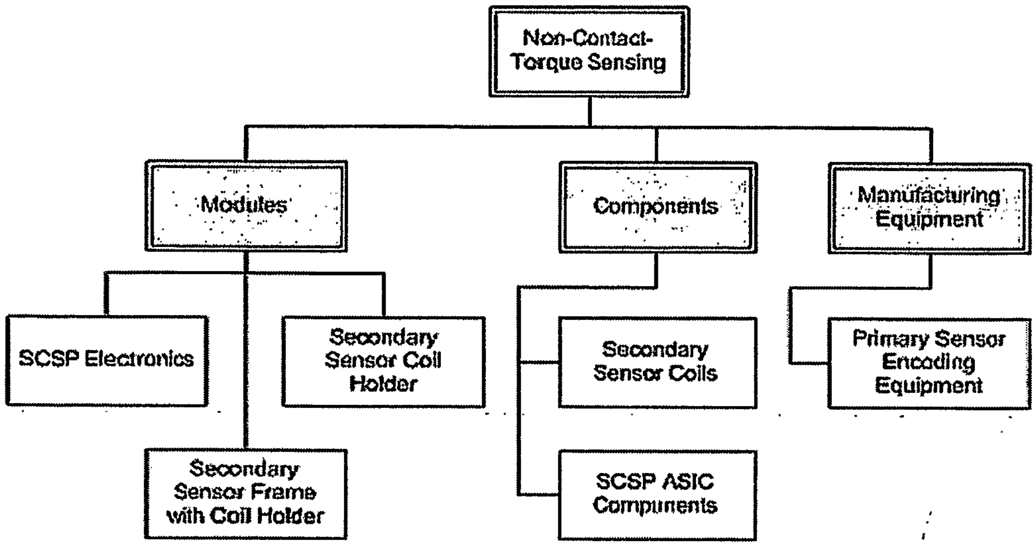
Sensor Components

The non-contact magnetostriction torque-sensor (NCT-Sensor) consists, according to an exemplary embodiment of the present invention, of three main functional elements: The ***Primary Sensor***, the ***Secondary Sensor***, and the ***Signal Conditioning & Signal Processing*** (SCSP) electronics.



Depending on the application type (volume and quality demands, targeted manufacturing cost, manufacturing process flow) the customer can chose to purchase either the ***individual components*** to build the sensor system under his own management, or can subcontract the production of the ***individual modules***.

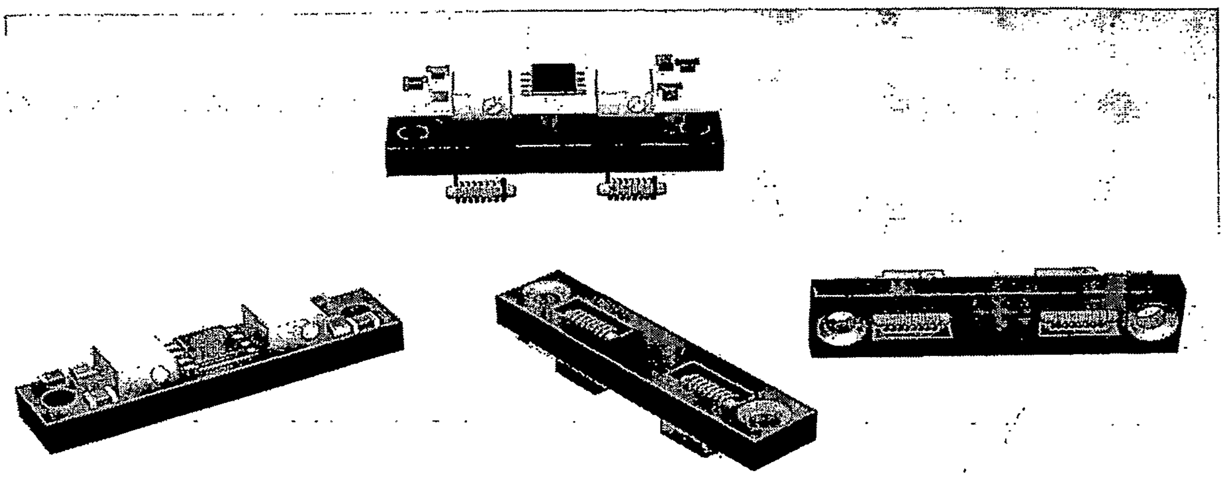
In cases where the annual production target is in the thousands of units it may be more efficient to integrate the "primary-sensor magnetic-encoding-process" into the customers manufacturing process. In such a case the customer needs to purchase application specific "magnetic encoding equipment".



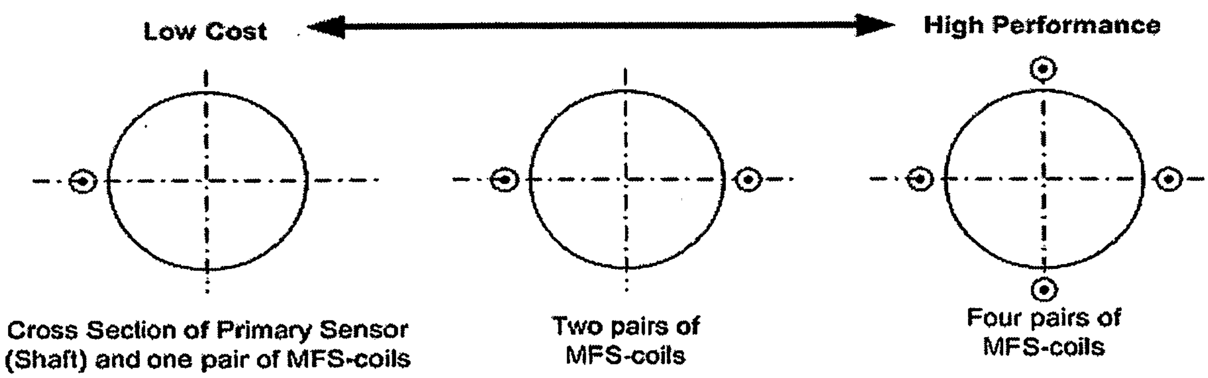
In high volume applications, where cost and the integrity of the manufacturing process are critical, it is typical that NCTE supplies only the individual basic components and equipment necessary to build a non-contact-torque sensor:

- ☐ ICs (surface mount packaged, Application-Specific Electronic Circuits)
- ☐ MFS-Coils (as part of the Secondary Sensor)
- ☐ Sensor Host Encoding Equipment (to apply the magnetic encoding on the shaft = Primary Sensor)

Depending on the required volume, the MFS-Coils can be supplied already assembled on a frame, and if desired, electrically attached to a wire harness with connector. Equally the SCSP (Signal Conditioning & Signal Processing) electronics can be supplied fully functional in PCB format, with or without the MFS-Coils embedded in the PCB.



The number of required MFS-coils is dependent on the expected sensor performance and the mechanical tolerances of the physical sensor design. In a well designed sensor system with perfect Sensor Host (SH or magnetically encoded shaft) and minimal interferences from unwanted magnetic stray fields, only 2 MFS-coils are needed. However, if the SH is moving radial or axial in relation to the secondary sensor position by more than a few tenths of a millimeter, then the number of MFS-coils need to be increased to achieve the desired sensor performance.

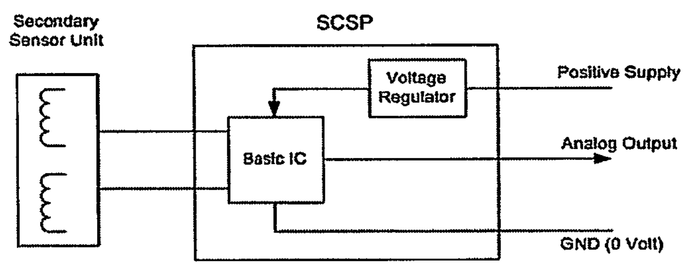


Control and/or evaluation circuitry

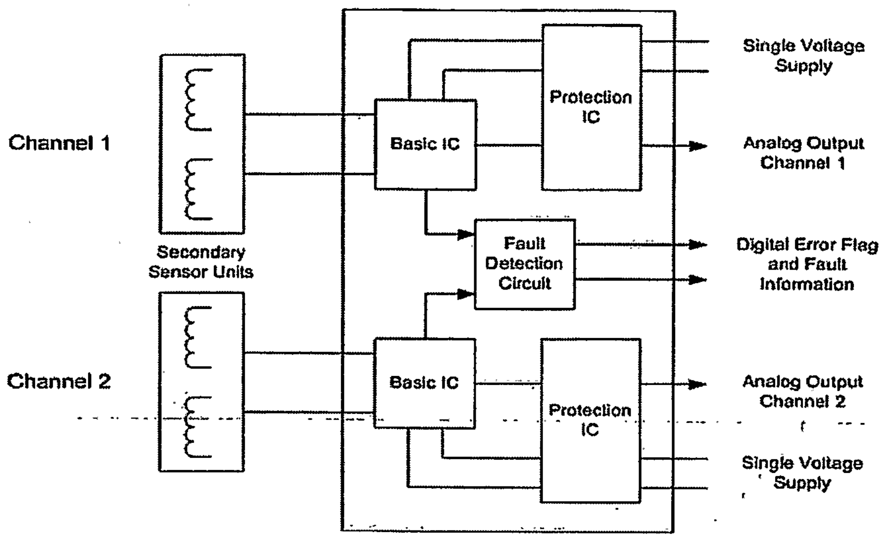
The SCSP electronics, according to an exemplary embodiment of the present invention, consist of the NCTE specific ICs, a number of external passive and active electronic circuits, the printed circuit board (PCB), and the SCSP housing or casing. Depending on the environment where the SCSP unit will be used the casing has to be sealed appropriately.

Depending on the application specific requirements NCTE (according to an exemplary embodiment of the present inevention) offers a number of different application specific circuits:

- ☐ Basic Circuit
- ☐ Basic Circuit with integrated Voltage Regulator
- ☐ High Signal Bandwidth Circuit
- ☐ Optional High Voltage and Short Circuit Protection Device
- ☐ Optional Fault Detection Circuit



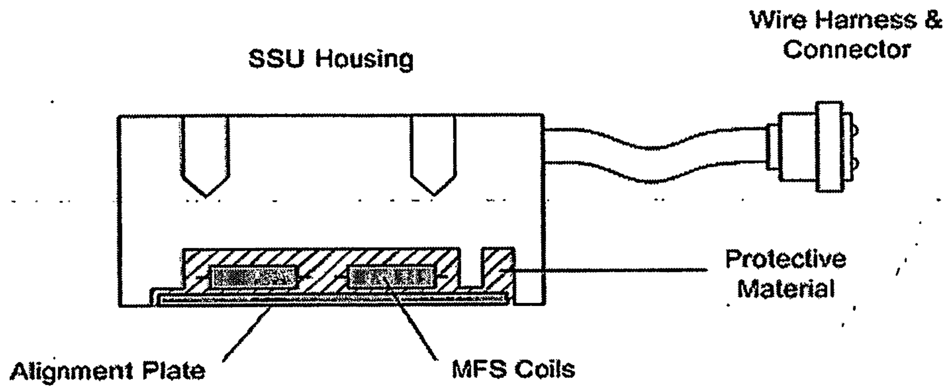
Example 1: Single channel, low cost sensor electronics solution



Example 2: Dual channel, short circuit protected system design with integrated fault detection. This design consists of 5 ASIC devices and provides a high degree of system safety. The Fault-Detection IC identifies when there is a wire breakage anywhere in the sensor system, a fault with the MFS coils, or a fault in the electronic driver stages of the "Basic IC".

Secondary Sensor Unit

The Secondary Sensor consists of the elements: One to eight **MFS** (Magnetic Field Sensor) Coils, the **Alignment- & Connection-Plate**, the wire harness with connector, and the **Secondary-Sensor-Housing**.



The MFS-coils are mounted onto the alignment-Plate. Usually the Alignment-Plate allows that the two connection wires of each MFS-Coil are soldered / connected in the appropriate way. The wire harness is connected to the alignment plate. This, completely assembled with the MFS-Coils and wire harness, is then embedded or held by the Secondary-Sensor-Housing.

The main element of the MFS-Coil is the core wire, which has to be made out of an amorphous-like material.

Depending on the environment where the Secondary-Sensor-Unit will be used, the assembled Alignment Plate has to be covered by protective material. This material can not cause mechanical stress or pressure on the MFS-coils when the ambient temperature is changing.

In applications where the operating temperature will not exceed +110 deg C the customer has the option to place the SCSP electronics (ASIC) inside the secondary sensor unit (SSU). While the ASIC devices can operated at temperatures above +125 deg C it will become increasingly more difficult to compensate the temperature related signal-offset and signal-gain changes.

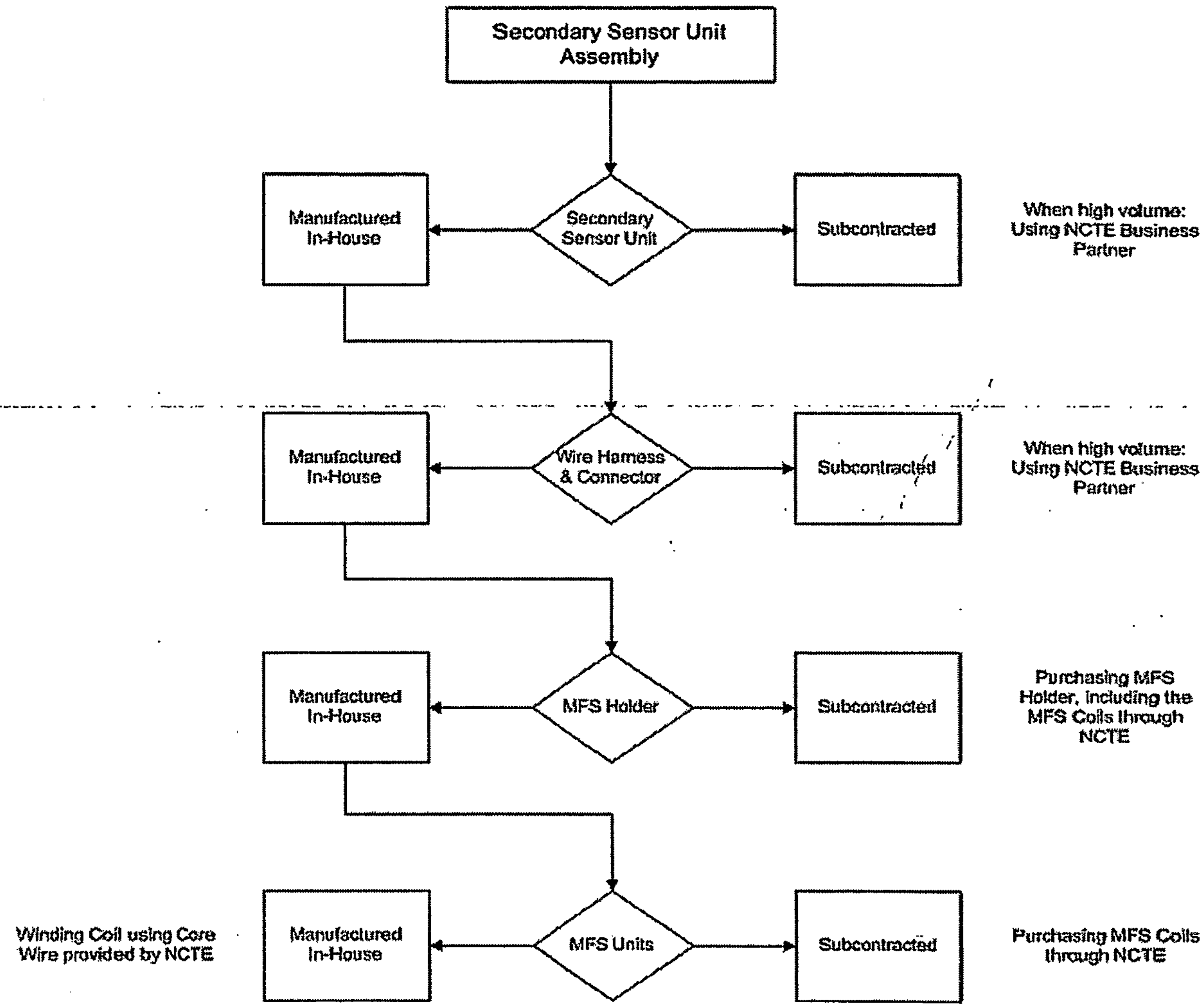
The recommended maximal cable length between the MFS-coils and the SCSP electronics is 2 meters. When using the appropriate connecting cable, distances of up to 10 meters are achievable. To avoid signal-cross-talk in multi-channel applications (two independent SSU's operating at the same Primary Sensor location = Redundant Sensor Function), specially shielded cable between the SSU's and the SCSP Electronics should be considered.

When planning to produce the Secondary-Sensor-Unit (SSU) the producer has to decide which part / parts of the SSU have to be purchased through subcontracting and which manufacturing steps will be made in-house.

Secondary Sensor Unit Manufacturing Options

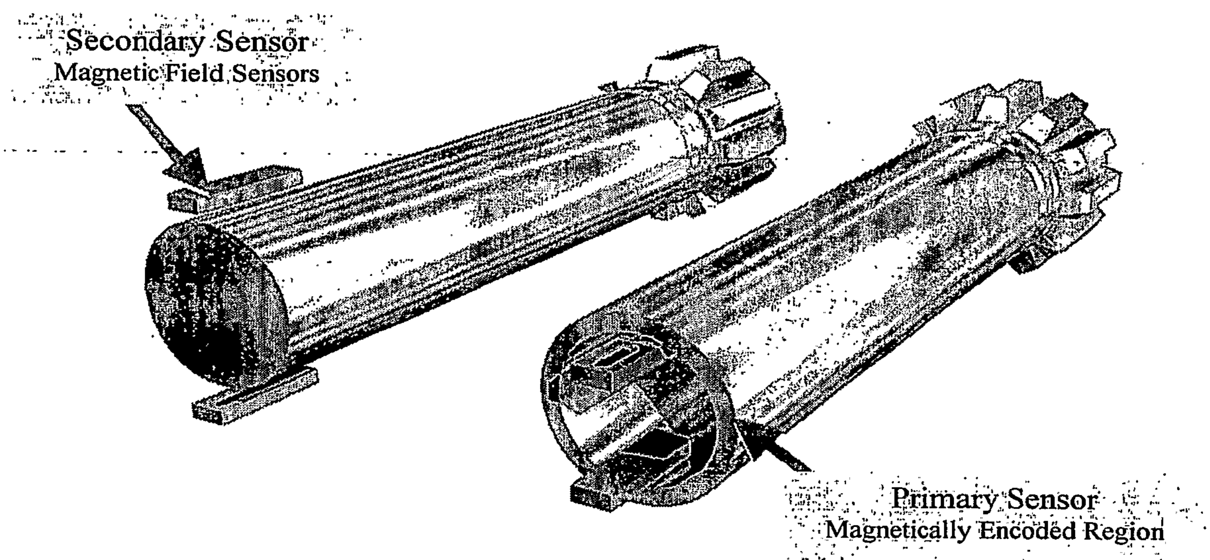
When integrating the NCT-Sensor into a customized tool or standard transmission system then the systems manufacturer has several options to choose from:

- ☐ custom made SSU (including the wire harness and connector)
- ☐ selected modules or components; the final SSU assembly and system test may be done under the customer's management.
- ☐ only the essential components (MFS-coils or MFS-core-wire, Application specific ICs) and will produce the SSU in-house.

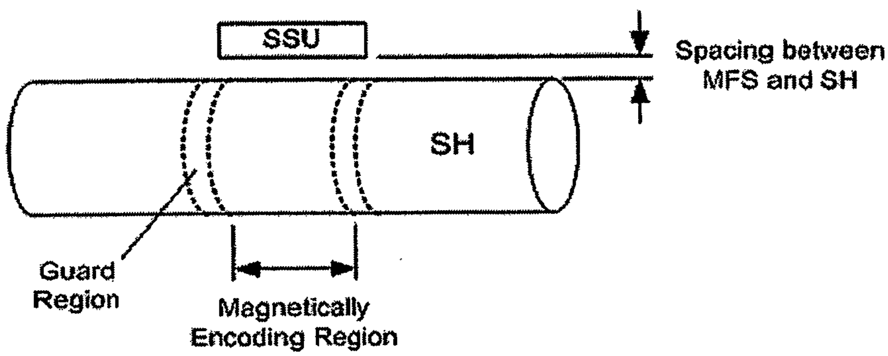

Secondary Sensor Unit Assembly
Manufactured In-House
Secondary Sensor Unit
Subcontracted
When high volume: Using NCTE Business Partner
Manufactured In-House
Wire Harness & Connector
Subcontracted
When high volume: Using NCTE Business Partner
Manufactured In-House
MFS Holder
Subcontracted
Purchasing MFS Holder, including the MFS Coils through NCTE
Winding Coil using Core Wire provided by NCTE
Manufactured In-House
MFS Units
Subcontracted
Purchasing MFS Coils through NCTE

Primary Sensor Design

The SSU (Secondary Sensor Units) can be placed outside the magnetically encoded SH (Sensor Host) or, in case the SH is hollow, inside the SH. The achievable sensor signal amplitude is of equal strength but has a much better signal-to-noise performance when placed inside the hollow shaft.



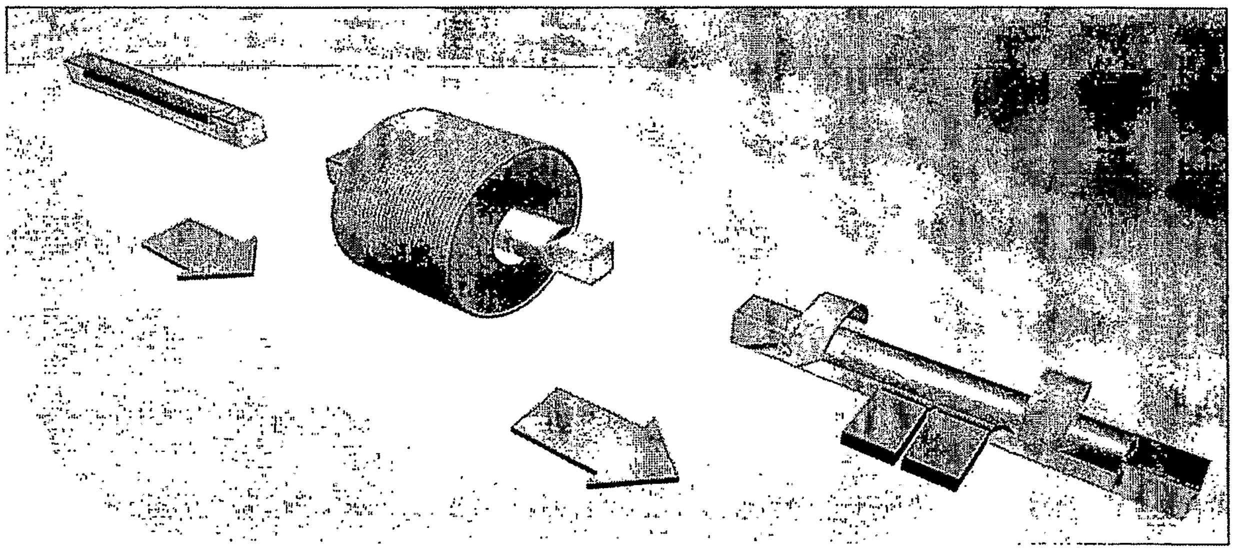
Improved sensor performances may be achieved when the magnetic encoding process is applied to a straight and parallel section of the SH (shaft). For a shaft with 15 mm to 25 mm diameter the optimal minimum length of the Magnetically Encoded Region is 25 mm. The sensor performances will further improve if the region can be made as long as 45 mm (adding Guard Regions). In complex and highly integrated transmission (gearbox) systems it will be difficult to find such space. Under more ideal circumstances the Magnetically Encoding Region can be as short as 14 mm, but this bears the risk that not all of the desired sensor performances can be achieved.



The spacing between the SSU (Secondary Sensor Unit) and the Sensor Host surface, according to an exemplary embodiment of the present invention, should be held as small as possible to achieve the best possible signal quality.

Primary Sensor Encoding Equipment

Depending on which magnetostriction sensing technology will be chosen, the Sensor Host (SH) needs to be processed and treated accordingly. The technologies vary by a great deal from each other (ABB, FAST, FT, Kubota, MDI, NCTE, RM, Siemens, ...) and so does the processing equipment required. Some of the available magnetostriction sensing technologies don't need any physical changes to be made on the SH and rely only on magnetic processing (MDI, FAST, NCTE).



While the MDI technology is a two phase process, the FAST technology is a three phase process, and the NCTE technology a one phase process, called PCM Encoding.

Note: Be aware that after the magnetic processing, the Sensor Host (SH or Shaft), has become a "precision measurement" device and has to be treated accordingly. The magnetic processing should be the very last step before the treated SH is carefully placed in its final location.

The magnetic processing should be an integral part of the customer's production process (in-house magnetic processing) under the following circumstances:

- ☐ High production quantities (like in the thousands)
- ☐ Heavy or difficult to handle SH (e.g. high shipping costs)
- ☐ Very specific quality and inspection demands (e.g. defense applications)

In all other cases it may be more cost effective to get the SH magnetically treated by a qualified and authorized subcontractor, such as NCTE. For the "in-house" magnetic processing dedicated manufacturing equipment is required. Such equipment can be operated fully manually, semi-automated, and fully automated. Depending on the complexity and automation level the equipment can cost anywhere from EUR 20k to above EUR 500k.

In this application, there are a number of "new" acronyms used as otherwise some explanations and descriptions may be difficult to read. While the acronyms "ASIC", "IC", and "PCB" are already market standard definitions, there are many new terms that have been created in relation to the magnetostriction based NCT sensing technology. It should be noted that in this application, when there is a reference to NCT technology, it is referred to exemplary embodiments of the present invention.

Acronym	Description	Category
ASIC	Application Specific IC	Electronics
DF	Dual Field	Primary Sensor
EMF	Earth Magnetic Field	Test Criteria
FS	Full Scale	Test Criteria
Hot-Spotting	Sensitivity to nearby Ferro magnetic material	Specification
IC	Integrated Circuit	Electronics
MFS	Magnetic Field Sensor	Sensor Component
NCT	Non Contact Torque	Technology
PCB	Printed Circuit Board	Electronics
PCME	Pulse Current Modulated Encoding	Technology
POC	Proof-of-Concept	
RSU	Rotational Signal Uniformity	Specification
SCSP	Signal Conditioning & Signal Processing	Electronics
SF	Single Field	Primary Sensor
SH	Sensor Host	Primary Sensor
SPHC	Shaft Processing Holding Clamp	Processing Tool
SSU	Secondary Sensor Unit	Sensor Component

According to an exemplary embodiment of the present invention, there is provided a torque sensor, comprising:

a first sensor element with a magnetically encoded region; and

a second sensor element with at least one magnetic field detector;

wherein the first sensor element has a surface;

wherein, in a direction essentially perpendicular to the surface of the first sensor element, the magnetically encoded region of the first sensor element has a magnetic field

structure such that there is a first magnetic flow in a first direction and a second magnetic flow in a second direction;

wherein the first direction is opposite to the second direction;

wherein the first sensor element is a shaft;

wherein in a cross-sectional view of the shaft, there is a first circular magnetic flow having the first direction and a first radius and a second circular magnetic flow having the second direction and a second radius; and

wherein the first radius is larger than the second radius.

Claims

1. Torque sensor, comprising:
a first sensor element with a magnetically encoded region; and
a second sensor element with at least one magnetic field detector;
wherein the first sensor element has a surface;
wherein, in a direction essentially perpendicular to the surface of the first sensor element, the magnetically encoded region of the first sensor element has a magnetic field structure such that there is a first magnetic flow in a first direction and a second magnetic flow in a second direction; and
wherein the first direction is opposite to the second direction.

2. Torque sensor according to claim 1,
wherein the first sensor element is a shaft; and
wherein in a cross-sectional view of the shaft, there is a first circular magnetic flow having the first direction and a first radius and a second circular magnetic flow having the second direction and a second radius;
wherein the first radius is larger than the second radius.

3. Method of magnetizing a metallic body element, the method comprising:
applying at least two current pulses to the metallic body element such that in a direction essentially perpendicular to a surface of the metallic body element, a magnetic field structure is generated such that there is a first magnetic flow layer in a first direction and a second magnetic flow layer in a second direction;
wherein the first direction is opposite to the second direction.

4. Method according to claim 3,
wherein, in a time versus current diagram, each of the at least two current pulses has a fast raising edge which is essentially vertical and has a slow falling edge.

5. Shaft for a magnetic sensor having, in a cross section thereof, at least two circular magnetic loops running in opposite directions.

6. Shaft according to claim 5, wherein the at least two circular magnetic loops are arranged concentrically.

7. Electrode system for applying current surges to a shaft,
wherein the electrode system comprises at least two groups of electrodes, each comprising a plurality of electrode pins;

wherein the electrode pins of each electrode are arranged in a circle such that the shaft is contacted by the electrode pins of the electrode at a plurality of contact points at an outer circumferential surface of the shaft.

EPO - Munich
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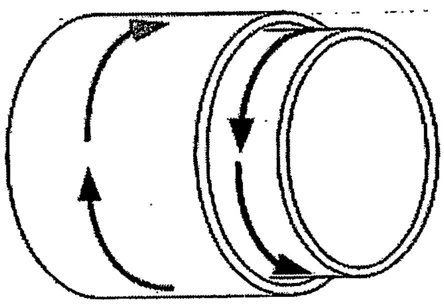
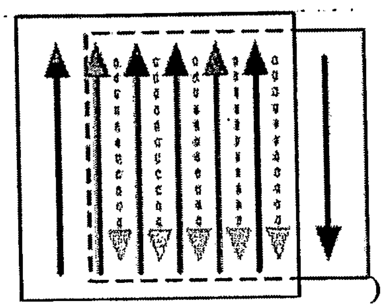
30. Dez. 2003

Abstract

The present invention relates to a torque sensor, comprising a first sensor element with a magnetically encoded region and a second sensor element with at least one magnetic field detector. The first sensor element has a surface. In a direction essentially perpendicular to the surface of the first sensor element, the magnetically encoded region of the first sensor element has a magnetic field structure such that there is a first magnetic flow in a first direction and a second magnetic flow in a second direction, wherein the first direction is opposite to the second direction.

(Fig. for abstract:

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